Northern California

Geology of Northern California

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Standing more than 10,000 feet (3,000 m) above the surrounding terrain, Mt. Shasta is the largest volcano in northern California and symbolizes the dynamic geologic processes that have shaped a spectacular landscape.


U.S. Department of the Interior
U.S. Geological Survey
National Elevation Data Set Shaded Relief of California
USGS
science for a changing world
Geography - The National Map

ESSENTIAL QUESTIONS TO ASK

Northern California.1 Introduction

- *What are northern California's physiographic provinces?*
- *What is the Farallon subduction zone?*
- *What two types of plate boundaries exist in northern California today?*
- *What are terranes, how do they originate, and why are they important in northern California?*

Northern California.2 The Sierra Nevada: California's Geologic Backbone

- *What is the Sierra Nevada batholith?*
- *What kinds of rocks surround the Sierra Nevada batholith?*
- *When and how was the modern Sierra Nevada uplifted?*
- *What types of gold deposits occur in the Sierra Nevada?*
- *What is the Mother Lode?*

Northern California.3 The Klamath Mountains

- *In what ways are the Klamath Mountains and the Sierra Nevada similar?*
- *What kinds of rocks comprise the ophiolites in the Klamath Mountains and what tectonic events do they signify?*
- *What mineral resources occur in the Klamath Mountains?*

Northern California.4 The Great Valley

- *What factors have led to the formation of fertile soils in the Great Valley?*
- *What was the origin of the sedimentary rocks in the Great Valley Sequence?*
- *What is the origin of the natural gas produced in the Great Valley?*
- *Why is the Great Valley so prone to chronic flooding?*

Northern California.5 The Northern Coast Ranges

- *What is the Franciscan complex and how did it form?*
- *How did the San Andreas fault system originate?*
- *What is the Salinian block?*
- *How old are the northern Coast Ranges and what tectonic forces elevated them?*

Northern California.6 Volcanoes of the Cascade Range and Modoc Plateau

- *What California volcanoes are part of the Cascade Range?*
- *What is the Cascadia subduction zone?*
- *What kind of volcanic activity typifies the Cascade Range?*
- *Why is Mount Lassen an especially interesting volcano in the Cascade Range?*

Northern California.7 The Basin and Range of Northeast California

- *What tectonic forces are responsible for the pattern of alternating mountains and valleys in the Basin and Range province?*
- *What mountains and basins in northern California belong to the Basin and Range province?*

Northern California.8 The Northern California Ice Ages

- *During what time periods did northern California experience Ice Age conditions?*
- *What landscape features resulted from the Pleistocene Epoch glaciations in northern California?*
- *How did the Pleistocene landscape of northern California differ from the modern setting?*

Northern California.9 Northern California Earthquakes

- *What plate tectonic settings are associated with northern California earthquakes?*
- *What is the likelihood of another major earthquake in northern California?*
- *What might be the effects of a large northern California earthquake?*
- *Given the severity of the potential hazards, how can the effects of earthquakes be minimized in northern California?*

Northern California.10 Living on the Edge: Coastal Hazards in Northern California

- *In comparison to the coast of southern California, why is the northern California shoreline so rugged and scenic?*
- *What coastal hazards exist in northern California?*
- *How do human activities affect coastal hazards?*

Northern California.1 Introduction

California's Varied Landscape: California is arguably the best place in the world to study geology. Few areas of comparable size are as geologically varied, physiographically diverse, or so spectacularly scenic as the Golden State. California's abundant natural resources reflect in large measure its rich geological history, and earthquakes, floods, and mass wasting events underscore the importance of ongoing geologic processes for residents and visitors. With the boundary between two of the largest lithospheric plates on the planet running for more than 1,300 kilometers along the western side of the state, California is an outstanding natural laboratory for studying Earth processes and plate interactions.

During the 1960s and 1970s, our understanding of earth dynamics shifted dramatically as the modern theory of plate tectonics was developed and refined. Many of the new concepts of that era either were developed in California or were specifically formulated to explain and/or reinterpret its incredibly varied geological features. Today, with a new theoretical framework and vastly improved tools for exploration and analysis, scientists continue to consider California a geologic paradise.

The rocks in California tell an amazing story of the evolution of land and life at the edge of North America. Although it would require many years to explore all the geologic wonders in California, a first course in physical geology is an excellent start to a lifetime of fascinating adventure in the Golden State. The purpose of this chapter is threefold: (1) to introduce the broader aspects of California's geologic setting, (2) to outline the major tectonic events that have shaped its landscape over geologic time, and (3) to examine the impacts on humans of the state's ongoing geologic evolution. I also hope you will consider this chapter an invitation to begin your own lifelong exploration of one of the most magnificent landscapes in the world.

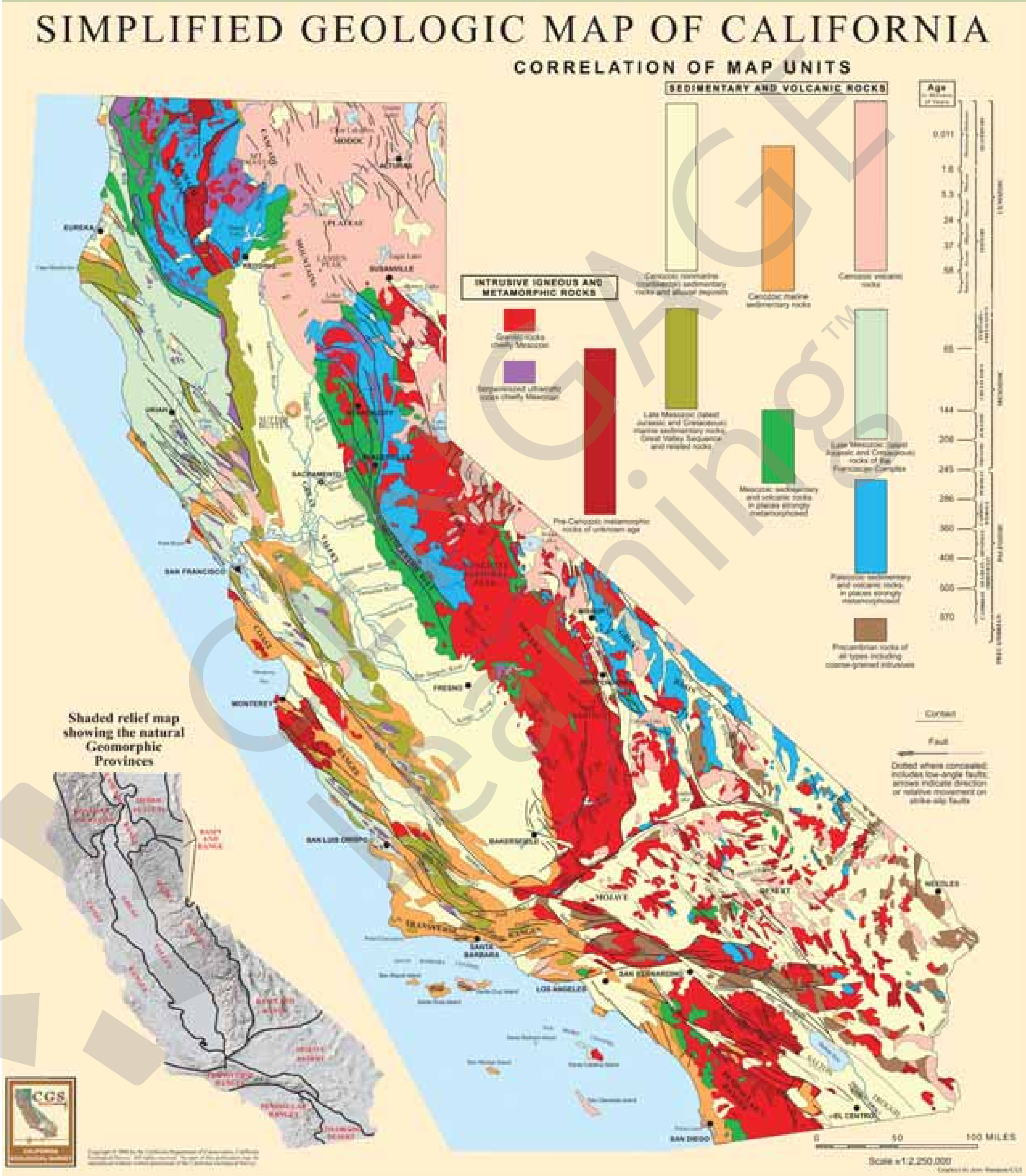
California's Physiographic Provinces: The California landscape can be divided into a dozen regions of distinctive and characteristic geology, landforms, climate, geomorphic trends, soils and vegetation, and drainage. These natural areas are known as **physiographic provinces**. After the geologic alignment of the state's major mountain systems, most of the geomorphic provinces are oriented in a northwest-to-southeast trend (Figure NC.1). Hence some of the provinces, such as the Sierra Nevada and the Coast Ranges, extend from the northern part of the state to the southern portion. For the purposes of the present discussion, we will arbitrarily define northern California as the region between Monterey Bay (latitude approximately 36.5° N) and the California–Oregon border. In this portion of California, seven natural physiographic provinces comprise the landscape: the northern Sierra Nevada, the northern Coast Ranges, the northern Central Valley, the Klamath Mountains, the Cascade Range, the Modoc Plateau, and portions of the Basin and Range. Though there are consistent geologic patterns within each of these regions that make them distinctive and identifiable, none can be regarded as simple or monotonous. Each of the physiographic provinces in northern California is a varied and fascinating geological realm with endless opportunities for applying the knowledge you have gained in your physical geology course. Collectively, they represent a region of such complex origin that scientists have yet to develop completely satisfactory explanations of all of the geologic features in this varied terrain. The common attribute of all the physiographic provinces of northern California is that, one way or another, each reflects the consequences of plate tectonic interactions along the western margin of North America over the past 500 million years.

Geologic Map of California: Geologic maps are indispensable assets in exploring the natural history and geologic setting of any region. Such maps show the distribution of rock types and ages on the surface, along with information about the orientation of the various rock bodies, the nature of their contact with adjacent rock masses, and the trends and extent of geologic structures such as faults and folds. This information is essential in unraveling the geologic history of a region because it reveals spatial patterns in the distribution of rocks of various types, ages, and degree of deformation that reflect the tectonic and geologic events of the past. In addition, geologic maps are of critical importance in locating surface and subsurface deposits of earth resources and in identifying the areas most susceptible to various geologic hazards.

Figure NC.1 The Physiographic Provinces of California

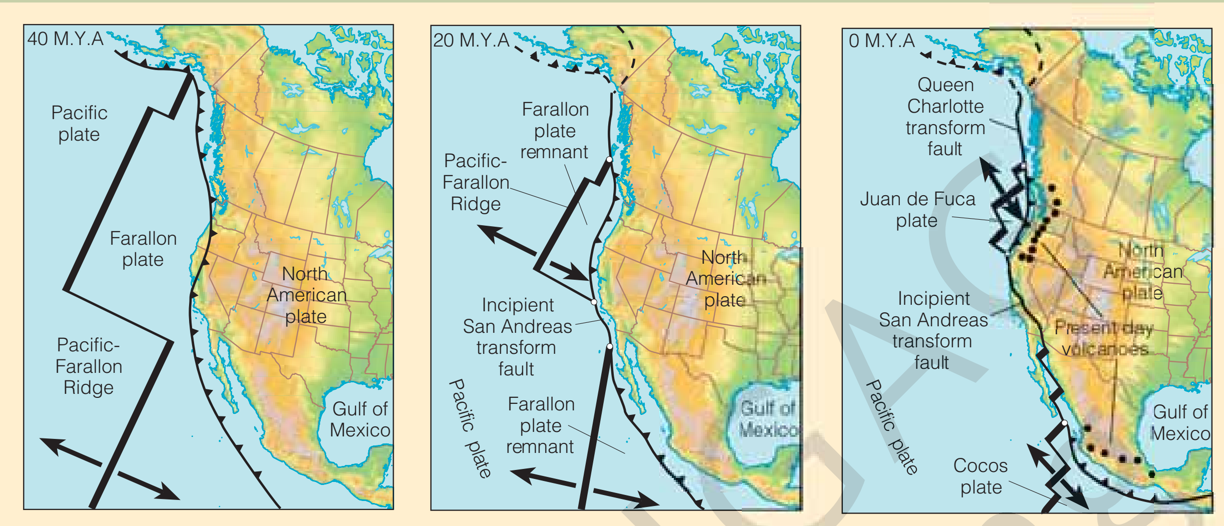
Map courtesy of the U.S. Geological Survey

► **Figure NC.2** Geological Map of California



The geologic map of California (Figure NC.2) has been compiled by the California Geological Survey over many decades of geologic mapping. This map is scaled to show the entire state and, as such, it portrays only the broader distribution of various California rocks and structures. Nonetheless, you will notice at a glance the strong similarity between the physiographic provinces in California and the distribution of various rock types. For example, notice the similarity in location, trend, and extent of the Sierra Nevada province and the large area of red, blue, and green

▶ **Figure NC.3** Interactions between The Farallon, Pacific, and North American plates over the past 40 million years.



colors on the geologic map. These colors represent the Mesozoic-age plutonic igneous rocks that comprise the core of the Sierra Nevada (red) and the older rocks that were metamorphosed by the emplacement of the magma (blue and green). A very similar pattern is observed in the Klamath Mountains physiographic province northwest of the Sierra Nevada, suggesting that the two regions share some common geologic traits. The similarity between the physiographic provinces of California and the distribution of various types and ages of rock in the state underscores the importance of the geologic foundation in shaping the character of the landscape.

The Westward Migration: For the past 500 million years convergent plate tectonic interactions have prevailed along the western margin of North America. Early in the Mesozoic Era, about 200 million years ago, the rate of plate convergence increased significantly as the ancient supercontinent of **Pangaea** began to break up. The North American plate separated from the northern part of the supercontinent via the opening of the Atlantic Oceanic basin. Seafloor spreading in this basin propelled the North American plate to the west while the Eurasia and African plates moved in the opposite direction. Several different oceanic plates were subducted under the leading edge of the North American plate as it slowly moved west. The last and largest of the oceanic plates to descend beneath North America was the **Farallon plate**, remnants of which still exist along the western margin of North and Central America. This plate tectonic interaction along the western edge of North America produced the **Farallon subduction zone**, which was established in mid-Mesozoic time and persisted from some 160 million years ago until about 30 million years ago. Many of the major geologic trends in California are the result of this long history of plate convergence.

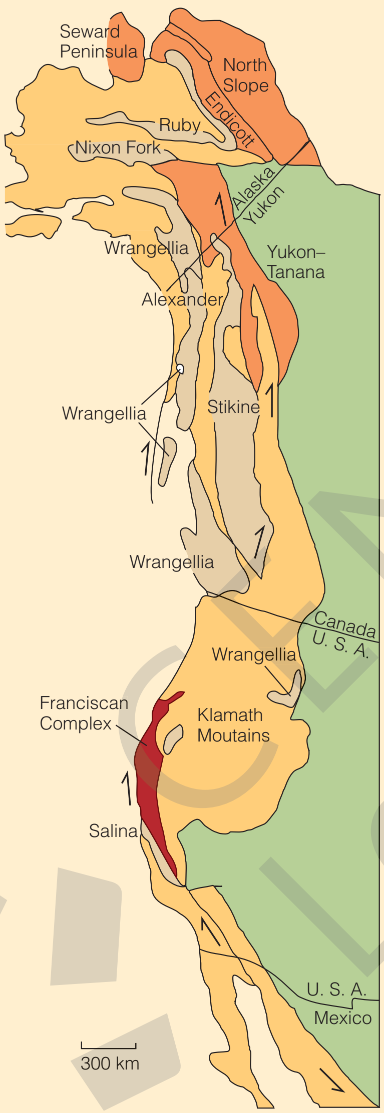
Origin of the Modern Transform Plate Boundary: The Farallon plate originated at an oceanic ridge to the west and southwest of North America. On the other side of that ancient spreading center, the Pacific plate was sliding to the west, while the Farallon plate moved in the opposite direction toward the advancing margin of North America. A little less than 30 million years ago, the western edge of North America collided with, and eventually overran, the Pacific-Farallon ridge near the latitude of modern Los Angeles. As a consequence of this collision, the North American plate came into contact with the Pacific plate (Figure NC.3).

The collision between North America and the Pacific-Farallon ridge ended plate convergence in the California region and established the modern **transform plate boundary**. After the initial collision of the ridge and the continent, the transform plate boundary expanded north and south as North America continued moving west, overrunning more of the ridge in the process (Figure NC.4). The relatively small Cocos, Rivera, and Juan de Fuca plates represent modern remnants of the ancient Farallon plate. The famous San Andreas fault system developed as a consequence of the transform plate boundary between the North America and the Pacific plates.

The geologic setting of modern northern California is thus influenced by two different kinds of boundaries between the North American and oceanic plates to the west: a transform boundary from Monterey Bay to Cape Mendocino and a remnant convergent boundary to the north. We will explore the consequences of these interactions in more detail in the sections that follow.

California and Accreted Terranes: One of the consequences of the long history of plate convergence along the western margin of North America was the accretion of numerous blocks of rock to stable crust of the continent. Such blocks added to the edge of a continent by plate convergence are known as **accretionary terranes**, or simply **terranes**. Five hundred million years ago, there was no land where the Pacific Coast now stands. The crust of California

▶ **Figure NC.4** Major terranes of western North America. In addition to the Franciscan Complex and the Salinian block illustrated here, dozens of smaller terranes have been identified in northern California.



has since been assembled in piecemeal fashion as seamounts, island arcs, coral reefs, and small continental blocks that were carried on subducting oceanic plates collided with the western edge of the continent and were embedded into the existing margin. The rocks in the various terranes were metamorphosed and deformed as each was sutured into North America like pieces of a mosaic. In this manner, North America grew incrementally westward with the addition of each fragment. Geologists are in general agreement that about 100 such terranes were accreted to the western margin of North America since the breakup of Pangaea about 200 million years ago. Several others were added in earlier accretionary events in the Paleozoic Era, before North America separated from Pangaea. It was not until Cenozoic time that all of the terranes were in place along the Pacific Coast and the modern California landscape began to emerge.

California, as a whole, therefore represents a geologic collage, an amalgam of pieces assembled through the convergence of plates along the west edge of North America over the past 500 million years. Northern California is especially intriguing because here both a remnant of an ancient convergent boundary and the modern transform boundary to the south continue to shape the landscape. It is not surprising that geologists find northern California such a fascinating region. It is a place where the geologic past meets the dynamic present, and there is no place in the world better suited for geologic exploration. Let's look a little closer.

Section Northern California.1 Summary

- The geology and landscape of northern California is extremely varied, with seven different physiographic provinces, each with distinctive rock assemblages and geologic histories.
- Convergent plate boundaries have existed for 500 million years in the northern California region. After North America separated from Pangaea early in the Mesozoic Era, the rate of convergence increased as several oceanic plates were subducted under the west-moving continent.
- The subduction of the Farallon plate in the Mesozoic Era resulted in many of the geologic trends that can be observed in modern California. About 30 million years ago, plate convergence ended as the transform boundary between the Pacific and North American plates began to develop. The unique geologic setting of modern northern California is shaped by both a remnant of the Mesozoic subduction zone and the continuing evolution of the more recent transform plate boundary.

Northern California.2 The Sierra Nevada: California's Geologic Backbone

The Sierra Nevada is California's best known mountain system. Stretching for more than 700 kilometers from Lake Almanor in the north to Tehachapi in the south, this northwest-trending mountain system is home to three national parks and the highest peak in the coterminous United States at Mount Whitney (14,495 feet/4,418 meters above sea level). Winter storms passing east from the Pacific Ocean over the high Sierra Nevada produce heavy snowfall that is an essential supply of water to the entire state. Materials released from the weathering of Sierra Nevada bedrock help sustain the fertility of California's rich agricultural soils. It was in the Sierra Nevada foothills that gold was discovered in the 1800s, and the course of California history was forever changed. Without the Sierra Nevada, California would simply not be California.

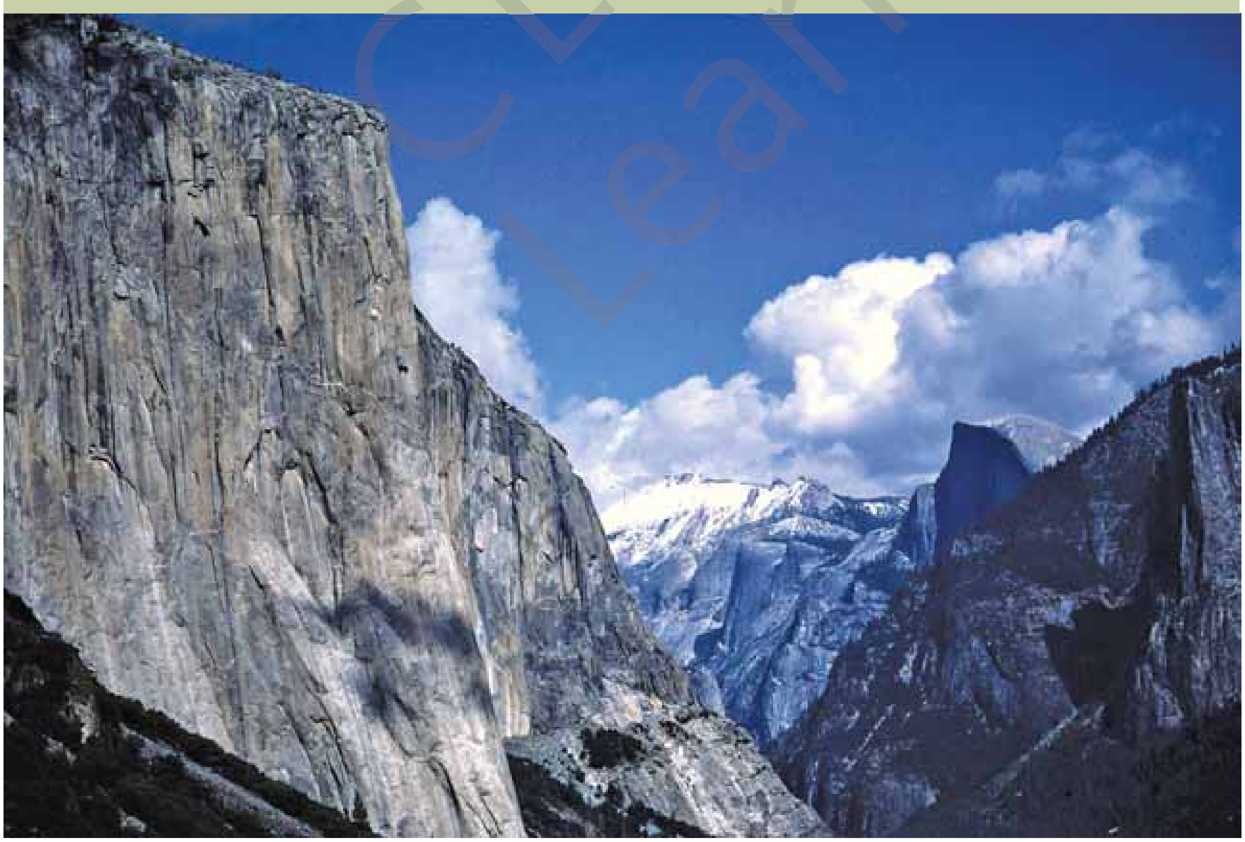
The bedrock of the Sierra Nevada is dominated by the Mesozoic Sierra Nevada **batholith**, one of the largest and most complex masses of granitic rock in the world. Adjacent to the batholith, and sometimes as **xenoliths** and **roof pendants** within it, are older Mesozoic and Paleozoic metamorphic rocks that were invaded by the subterranean magma. More recent episodes in the evolution of the Sierra Nevada are documented by Cenozoic **volcanic** and sedimentary rocks that rest on the granite-metamorphic basement.

The Sierra Nevada Batholith: The geologic map of California clearly indicates that the Mesozoic granite of the Sierra Nevada batholith comprises the core of the Sierra Nevada. Vast exposures of such light-colored **plutonic** rock in the high country of Yosemite, Kings Canyon, and Sequoia National Parks, is in part what led John Muir to refer to the Sierra as "the range of light" (Figure NC.5). The **Sierra Nevada batholith** is a complex assemblage of perhaps as many as 200 individual **plutons** representing magma bodies emplaced mostly between 140 million and 80 million years ago at depths of 10 to 30 kilometers beneath the surface. Most of the plutons comprising the Sierra Nevada batholith consist of **felsic** rock such as **granite**, rich in light-colored quartz, potassium feldspar, and sodium-rich plagioclase (Figure NC.6). Some of the plutons are richer in the darker ferromagnesian minerals and consist of rock more similar to **diorite** or **gabbro**.

The Sierra Nevada batholith represents the deep roots of a Mesozoic **volcanic arc** that developed **along** the western margin of North America above the Farallon subduction zone. In this ancient subduction zone, magma was produced by partial melting and migrated upward through older crustal material to build a chain of andesitic volcanoes that rivaled the modern Andes Mountains of South America. Recent geologic studies have revealed evidence of large **calderas** formed by explosive eruptions in this ancient volcanic chain. Late in the Cenozoic Era, the uplift of the Sierra Nevada resulted in the nearly complete erosion of the volcanic edifice that originally concealed the batholitic rocks. However, isolated remnants of the ancient volcanoes can still be seen in places along the crest of the range (Figure NC.7).

Paleozoic-Mesozoic Accretionary Terranes of the Northern Sierra Nevada: The magma that formed the Sierra Nevada batholith was emplaced into older rocks that either accumulated on the seafloor west of the margin of

► **Figure NC.5** Vast exposures of granitic rock characterize the Sierra Nevada, John Muir's "Range of Light".



▶ Figure NC.6 Close up of granite from the Sierra Nevada Batholith. Dark crystals are biotite and hornblende, white crytals are plagioclase and potassium feldspar, and the gray translucent crystals are quartz.

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▶ Figure NC.7 Dark-colored rocks of the Ritter Range in the eastern Sierra Nevada are remnants of the Mesozoic Sierra volcanic arc.

Dick Hilton

Paleozoic North America or were accreted to the edge of the continent in convergent plate interactions that preceded the Farallon subduction zone. These old rocks were deformed and metamorphosed during several different accretion events and altered by the heat and fluids associated with magma rising from the Farallon subduction zone in later Mesozoic time. Metamorphic rocks such as marble, slate, schist, **serpentinite**, and **greenstone** are common in the pre-batholithic terranes of the Sierra Nevada. Some of

▶ Figure NC.8 Folds in these Paleozoic sedimentary rocks along the Yuba River were developed during the collision between a block of oceanic rocks and western edge of North America in the Mesozoic Era.

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these rocks have been affected by multiple periods of metamorphism. In addition, these rocks are commonly folded and faulted by the compressional stress generated along ancient convergent plate boundaries (Figure NC.8).

It has taken geologists many decades to unscramble the complicated history recorded in the metamorphic rocks surrounding the Sierra Nevada batholith. Within the granitic core of the Sierra Nevada, exposures of these rocks are found as roof pendants and xenoliths (Figure NC.9) preserved in the plutonic rocks. In the foothills north and west of the batholithic core of the Sierra Nevada, extensive exposures of metamorphic rocks have revealed a complex history of metamorphism and accretion. Because there has been much greater Cenozoic uplift in the southern Sierra Nevada than in the north, erosion there has progressed to a deeper level in the crust and much of the older rock that formerly surrounded the granitic plutons has been removed.

Within the western foothills metamorphic belt, geologists have identified three primary units of metamorphosed rocks that are separated from each other by major **faults**. These faults probably were produced when seamounts, undersea volcanic arcs, oceanic crust, or other fragments of lithosphere collided with the edge of North America. The metamorphosed and deformed rocks comprising these

▶ **Figure NC.9** Dark-colored xenoliths in Sierra granite represent fragments of older rock assimilated into the magma prior to crystallization.

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terranes are almost entirely of oceanic origin, and generally older than the tectonic events that sutured them to the North American continent. Some represent mafic magma erupted by undersea volcanoes, and the characteristic **pillow structures** can still be observed (Figure NC.10). Other terranes include oceanic sedimentary rocks such as **chert**, **mudstone**, and **limestone** that have been metamorphosed to varying degrees. There is strong evidence that some of the accreted fragments traveled thousands of kilometers before the now-vanished plates carrying them sank into ancient subduction zones. **Ophiolites**, sequences of rocks representing oceanic lithosphere, are present in some terranes, and probably originated as fragments splintered from the descending oceanic plates sutured into the various terranes. Adding complexity to some of the terranes is the presence of **mélanges**, chaotic mixtures of deformed and metamorphosed rocks that are formed in subduction zone settings. We will learn more about ophiolites and mélanges when we explore the northern Coast Range, where they formed within the much younger Farallon subduction zone.

▶ **Figure NC.10** The rounded pillow structures in this outcrop of mildly metmorposed basalt in the western metmorphic belt indicate eruption of lava on the seafloor.

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Cenozoic Rocks of the Sierra Nevada: At the end of the Mesozoic Era about 65 million years ago, the Sierra Nevada was an elevated volcanic terrain perched on a complex basement comprised of older rocks intruded by the concealed Sierra Nevada batholith. As Cenozoic time (the Tertiary Period) began, igneous activity appears to have temporarily subsided in the Sierra region, and erosion was beginning to attack the summits of the dormant volcanoes. The volcanic highland extended into what is now western Nevada and the ancient shore of the ancestral Pacific Ocean was located along the foothills of the dormant volcanic arc in central California. Rivers draining the volcanic highland ran west across the site of the modern Sierra Nevada. These ancient rivers steadily wore away the volcanic bedrock, and transported great quantities of sediment to the ocean basin to the west. This long period of erosion in the Early Cenozoic Era produced a pronounced plain, which has since been elevated hundreds of feet above the floors of modern stream valleys in the Sierra Nevada region (Figure NC.11).

During the Eocene Epoch, about 50 million years ago, river-deposited sediments began to accumulate in the ancient river systems of the Sierra Nevada. In the stream channels, coarse gravel deposits formed. On the floodplains, fine sand, silt, and mud accumulated. These river-deposited sediments are still preserved in many places in the foothills of the Sierra Nevada as colorful exposures of conglomerate, sandstone, and mudstone. Geologic mapping in the early 1900s demonstrated that exposures of the ancient river gravels were aligned as elongated ribbons, indicating the location and drainage pattern of the 50-million-year-old river channels. Soon after the California Gold Rush began, prospectors discovered that some of the Eocene-age river gravels contained rich concentrations of gold in the form of nuggets, flakes, and fine particles. The richest gravel deposits became known as the "auriferous gravels." Such gold-bearing sediments were intensely mined and processed in the mid-1800s, primarily by washing away the weakly-cemented material with powerful steams of water and separating the small gold particles from the loosened sand, pebbles, and cobbles (Figure NC.12). Known as hydraulic mining, this process was phased out after 1884 because so much sediment had been washed from the Sierra slopes that agriculture and river navigation downstream in the Central Valley was being adversely affected. The best exposures of the auriferous gravels today are in the scars and excavations left from the hydraulic mining activities more than century ago.

During the Oligocene and Miocene Epochs, 35 million to 5 million years ago, volcanic activity resumed along what is today the crest of the Sierra Nevada and areas to the east. The initial eruptions were violent caldera-forming explosions that sent great flows of ash and fragments of volcanic

▶ **Figure NC.11** Beyond the deep canyon of the Yuba River on the Sierra Nevada west slope, the flat surface reflects a lengthy interval of erosion in the early Tertiary Period.

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▶ **Figure NC.12** Hydraulic mining in the Sierra Nevada involved washing Eocene sediments with powerful jets of water. Photo taken in 1905 at Junction City, California.

Bettmann/Corbis

▶ **Figure NC.13** Oligocene tuff near Soda Springs, California consists of ash partcles and white pumice fragments welded into a coherent rock.

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rock surging west through the canyons carved by the Eocene-age rivers. These **pyroclastic** deposits hardened into **tuffs** and **welded tuffs** that partially filled the ancient canyons (Figure NC.13). The later eruptions produced **basalt** flows, volcanic **breccias**, and volcanic mudflow deposits known as **lahars**. The Tertiary-age volcanic rocks completely filled some of the valleys of the western slope of the ancestral Sierra Nevada, forcing the ancient streams from their channels. In the past few million years, as the modern Sierra Nevada rose, vigorous down-cutting has left the erosion-resistant valley-filling Tertiary volcanic rocks perched high above modern river beds. Sinuous ridges capped by Tertiary volcanic rocks demonstrate the phenomena of **inverted topography** in many places in the Sierra foothills (Figure NC.14).

Recent Uplift of the Sierra Nevada: Though the rocks of the Sierra Nevada document a long history of geologic unrest, good evidence suggests that the modern range reflects a relatively recent pulse of uplift. Although the Sierra Nevada was probably an elevated tract of land since the mid-Mesozoic Era, recent geologic studies suggest that 5 million to 10 million years ago, the mountain system rose to its current elevation, primarily by westward tilting along **normal faults** located along the eastern escarpment. These faults, many of which remain active today, have uplifted and tilted the range to the west, producing a spectacularly rugged eastern escarpment and a gently inclined western slope. The steep eastern escarpment of the Sierra Nevada was a formidable barrier to the migration of people during the Gold Rush. Even today, only a few highways cross the crest of the northern Sierra Nevada through passes that range in elevation from more than 3,000 meters (9,945 feet) to just over 2,200 meters (7,259 feet) above sea level.

Geologists have not yet determined the precise cause for the recent uplift of the Sierra Nevada. The forces affecting the Sierra region are complicated by its proximity to regions of differing plate tectonic interactions. In the Basin and Range province to the east, tensional stresses are stretching the crust and producing the numerous normal faults, such as those along the eastern escarpment of the Sierra Nevada. To the west, the modern transform boundary between the Pacific and North American plate produces shear stresses that tend to move the Sierra Nevada block to the northwest. Recent studies also suggest that the dense lower crust of the southern Sierra Nevada may have been removed in late Cenozoic time by heat associated with material upwelling from the mantle. The removal of the dense root beneath the Sierra Nevada would have increased the buoyancy of the Sierra Nevada, causing it to rise. All of these factors may have been involved in the recent ascent of the Sierra Nevada. Whatever the precise cause of uplift may be, there is no doubt that it is still continuing. The northern portion of the Sierra Nevada is currently rising at a rate of 2 to 3 millimeters per year, estimated on the basis of stream incision rates and the increased tilt of ancient streambeds.

The Mother Lode: Gold and Geology of the Sierra Foothills: California is known as the "Golden State" for a reason: since the initial discovery in the mid-1800s, more than 115 million ounces of gold have been produced in the state, an amount equivalent to a volume of more than 190 cubic meters! At current prices, the cumulative value of California gold is more than $110 billion. Though gold has been found in many places in California, more than 75% of the amount recovered historically has come from the western foothills of the Sierra Nevada. It was also in this region that James Marshall first noticed the glittering nuggets in the American River in 1849 and ignited one of the most dramatic human migrations in history.

Figure NC.14 Inverted topography in the Sierra Nevada foothills is a common consequence of Miocene volcanic activity.

(a) (b) (c)

James S. Monroe

Gold was initially discovered in California as flakes and nuggets resting in modern river gravels. Such deposits are known as **placers**, and early miners invented several techniques to wash the gold particles from the loose river sediments. Soon, miners began to exhaust the placer deposits, and looked upstream from the gravel bars to find the source of the gold particles. They eventually found two sources for the placer gold. First, it was discovered that the Eocene-age river deposits were also rich in gold, particularly the lower channel-filling conglomerates. The "auriferous gravels" were more difficult to work than modern placers because they were more consolidated and generally exposed high above the modern streams. The invention of the hydraulic mining methods mentioned earlier helped to solve these difficulties, but the disastrous environmental consequences ended this practice in the 1880s. At the same time, prospectors discovered a second source of the placer gold: quartz veins in the bedrock in the western foothills metamorphic belt were found to contain large masses of native gold. Such gold-bearing quartz veins are called **lodes**, and the largest concentration of such ores in the Sierra foothills became known as the Mother Lode (Figure NC.15).

Geologists are still not certain about the source of all the gold in California, but the variety of ore types suggests multiple origins. Much of the Mother Lode gold may have been originally disseminated in the oceanic metamorphic rocks or in the younger igneous bodies. Some of the gold may have originated in the volatile gases associated with the granitic magma that intruded the Sierra Nevada basement during the Mesozoic era. During metamorphism related to either burial, tectonic accretion, or the emplacement of magma, hot fluids were introduced into the rocks of the Mother Lode belt and migrated through them along fractures, faults, or shear zones. Interactions between the circulating hot (hydrothermal) fluids and the metamorphic rock concentrated gold in the quartz-rich fluids. The hydrothermal fluids eventually cooled as they circulated through the fractured metamorphic rock, leaving veins of quartz laced with pure gold. When the gold-rich metamorphic rocks were eroded by Cenozoic-age streams, the heavy gold particles accumulated in nearby stream sediments and the less dense components of the bedrock were washed farther downstream.

In the Mother Lode belt, all three types of gold deposits—placers, auriferous gravels, and lodes—were present. It is not surprising that this region was the primary target of the Gold Rush prospectors and miners. Though production of gold in California fell dramatically after the 1860s, people occasionally still find gold in the streams of the Sierra Nevada.

► **Figure NC.15** Specimen of gold from Grass Valley, California. Inset map shows location of the Mother Lode region in the western foothills of the Sierra Nevada.

National Museum of Natural History, Specimen #R12197, Photo by D. Penland.

Section Northern California.2 Summary

- The Sierra Nevada is California's geological backbone and the largest mountain system in the state. It is a region of majestic scenery with three national parks, and the highest peaks in the coterminous United States.

- The core of the Sierra Nevada is comprised of the Sierra Nevada batholith, a large mass of granite emplaced into older rocks during the Mesozoic Era. Magma rising from the Farallon subduction zone constructed the batholith beneath a volcanic arc similar in origin to the modern Andes Mountains of South America. Surrounding the Sierra Nevada batholith are older metamorphic rocks in which numerous accreted terranes can be recognized. The metamorphic rocks form roof pendants and xenoliths in the batholithic rocks and extensive bedrock exposures in the western foothills. Cenozoic sedimentary and volcanic rocks record more recent periods of erosion and pyroclastic volcanic eruptions in the Sierra Nevada region.

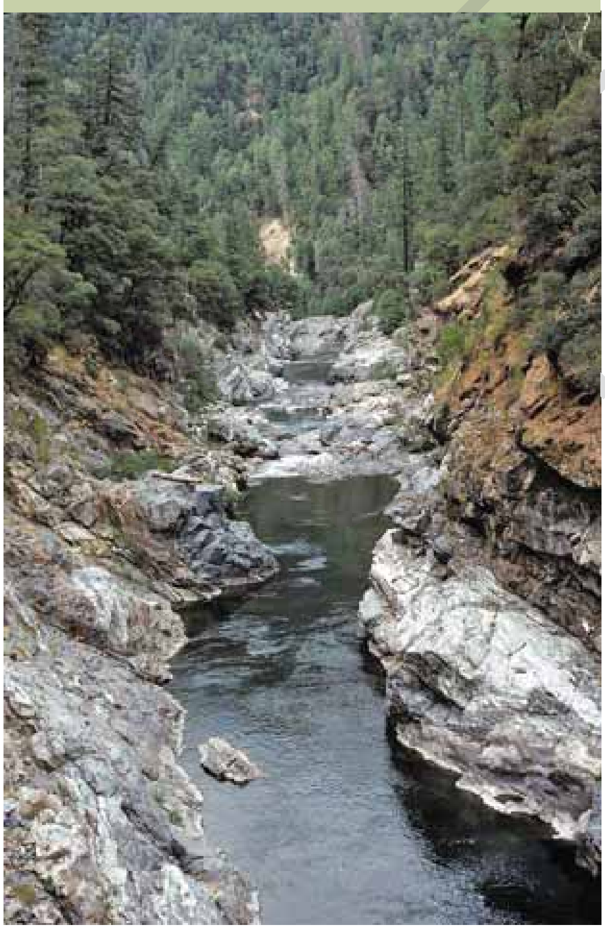
- Though the Sierra Nevada was an elevated region during the Mesozoic Era, the uplift of the modern mountains appears to have occurred primarily during the past 5 million to 10 million years, when normal faulting along the eastern side was initiated. The Sierra Nevada was lifted and tilted to west during this time, creating the gentle western slope and the abrupt eastern escarpment.

- Gold in the Sierra Nevada was concentrated in placers, Eocene stream gravels, and in lode deposits of the western foothills. In the famous Mother Lode belt of the Sierra Nevada foothills, all three types of gold deposits are present.

Northern California.3
The Klamath Mountains

The Klamath Mountain region is a rugged highland with a general elevation of 1,500 to 2,150 meters (5,000 to 7,000 feet) above sea level. This elevated terrain is deeply incised by the Klamath River and its major tributaries, the Trinity and Salmon Rivers. These rivers carry water to the Pacific Coast through winding and spectacularly rugged canyons (Figure NC.16). The deep river gorges separate the Klamath highland into several distinct mountain ranges, including the Trinity Alps and the Siskiyou, Marble, and Salmon Mountains, some of which extend northward into southern Oregon. These rugged mountains are generally lower than the Sierra Nevada to the south, with the maximum elevations reaching only about 2,750 meters (9,000 feet). The Klamath Mountains separate the northern Coast Range on the west from the volcanoes of the Cascade Range to the east. Unlike most other geologic provinces in northern California, the Klamath Mountains lack a prominent northwest orientation. Instead, the individual mountains in this province have a crude north-to-south alignment or a weakly curved trend.

▶ Figure NC.16 The rugged canyon of the Salmon River in the Klamath Mountains privince.

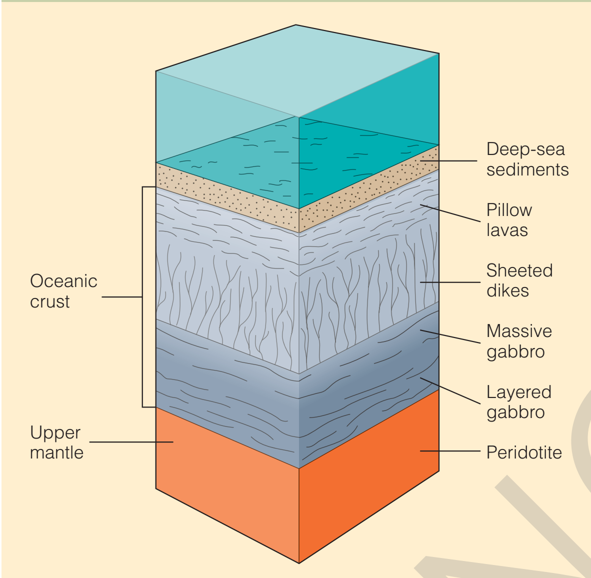


Dick Hilton

Even a quick glance at the geologic map of California reveals a strong similarity in outcrop colors and patterns of the Klamath Mountains region and the Sierra Nevada (see Figure NC.2). These similarities arise from comparable, though not identical, geologic histories in the two regions. In a general sense, the Klamath Mountains can be considered a northwest extension of the geologic trends of the Sierra Nevada. However, the continuity between the two regions is broken by the young volcanic rocks of the southern Cascade Range and by the sediments of the northern part of the Central Valley. The Klamath Mountains shares with the Sierra Nevada a long history of subduction-related accretion, beginning in the Paleozoic Era during which numerous oceanic terranes collided with the western edge of North America. The dozen or so terranes recognized by geologists in the Klamath region are separated from each other by major east-dipping fault zones. Granitic plutons of Mesozoic age were emplaced into the accreted terranes in several areas of the Klamath region, though such rocks are not as widespread in the Klamath region as they are in the Sierra Nevada. Both the Sierra Nevada and the Klamath Mountains experienced glaciation during the Pleistocene ice ages, though the lower elevations in the Klamath region resulted in smaller and less extensive glaciers. The Klamath Mountains region also experienced gold mineralization during the late Mesozoic Era, though none of the Klamath gold districts were as rich as the Mother Lode of the Sierra Nevada. Despite these similarities, the geologic story of the Klamath Mountains is not exactly the same as the Sierra Nevada. In the following sections, we focus on the unique attributes of the Klamath Mountains with respect to the similar Sierra Nevada.

Klamath Mountain Terranes and Ophiolites: In general, the Klamath Mountains region consists of numerous oceanic terranes representing fragments of crustal material that were embedded into the western margin of North America since Early Paleozoic time. The fragments include metamorphosed volcanic and sedimentary rocks that represent volcanic island arcs, submarine plateaus, reeflike bodies of limestone, and deep ocean sediments that were intensely deformed during accretion. It has taken geologists many years to unravel the complicated tectonic pattern in the Klamath Mountains, but it now appears that as many as a dozen different accreted terranes exist in the region. Some of these terranes no doubt represent the same fragments recognized in the western metamorphic belt of the Sierra Nevada. In general, the Klamath terranes become younger from east to west, a pattern that probably reflects the westward growth of North America through a series of plate collisions along the western edge of the continent. Some of the Klamath terranes may have originated thousands of kilometers from North America, whereas others were probably of local origin. Fossils discovered recently in the eastern Klamath terranes suggest that rocks as old as Late Precambrian, nearly 600 million years old, are included in the oldest accreted fragments.

▶ **Figure NC.17** Ophiolites are sequences of rock that represent oceanic lithosphere emplaced on land at convergent plate boundaries.



Of particular interest in the Klamath region are extensive exposures of **mafic** and **ultramafic** rocks known as ophiolites, sequences of igneous rocks thought by geologists to represent disrupted oceanic lithosphere. Ophiolites consist, in ascending order, of upper mantle **peridotite** overlain by layered and massive gabbro, sheeted basalt dikes, and basaltic pillow lavas (Figure NC.17). Ophiolite sequences can be emplaced on land during plate convergence simultaneously with the accretion process. As relatively thin and dense oceanic plates sink into subduction zones, fragments of the descending lithosphere are sometimes incorporated into the accretionary mass. The heat, pressure, and chemically active fluids that accompany plate convergence usually result in significant deformation, disruption, and metamorphism of the ophiolite sequences. In many exposures of the Klamath Mountains ophiolites, the mafic igneous rocks have altered into the metamorphic rock serpentinite, but careful studies can still reveal their origin as components of oceanic lithosphere. We will learn more about sepentinite in our examination of the northern Coast Ranges, where they are also abundant.

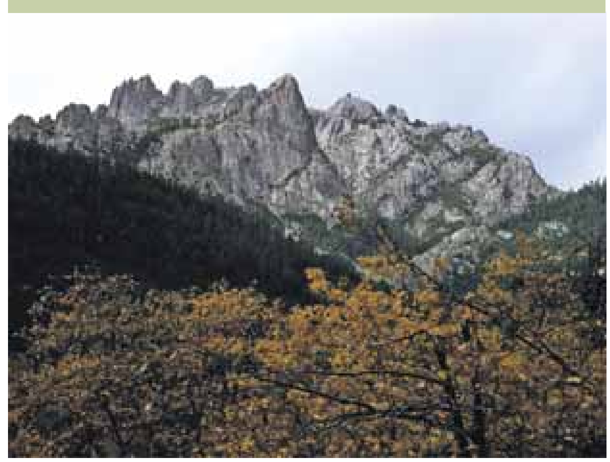
In the Klamath Mountains region, the Trinity and Josephine ophiolites are two of the largest and best known rock sequences of their type in the world. These two rock assemblages represent slivers of oceanic lithosphere that were incorporated into the accreted terranes at different times and different places in the Klamath region. The Trinity ophiolite is part of the Paleozoic–Early Mesozoic Eastern Klamath-Yreka **superterrane**, which is very similar to the Northern Sierra terrane of roughly the same age to the south. Most geologists feel that the Trinity and the Northern Sierra terranes were originally part of the same accreted oceanic plate. The mid-Mesozoic Josephine ophiolite is younger, about 162 million years old, and is exposed in the northwestern part of the Klamath region. The Josephine ophiolite may be in part equivalent to similar rocks in the western metamorphic belt of the Sierra Nevada. Neither the Josephine nor the Trinity ophiolite sequences are preserved in their entirety in the Klamath Mountains; they were disrupted and metamorphosed during accretion. Nonetheless, there is little doubt that ophiolites of the Klamath Mountains represent fragments of accreted oceanic lithosphere.

Mesozoic Plutonic Rocks of the Klamath Mountains: The Mesozoic Farallon subduction zone that generated great volumes of felsic magma in the Sierra Nevada region extends north to the Klamath region. However, the magma that intruded the Klamath basement was emplaced mostly as isolated plutons of relatively limited size and did not coalesce into larger masses similar to the Sierra Nevada batholith. The relatively small exposures of light-colored granitic rocks in the Klamath Mountains contrast with the darker metamorphic rock of the terranes to create spectacular landforms such as Castle Crags (Figure NC.18). The Mesozoic-age plutons of the Klamath region range in age from about 136 million to 174 million years, and tend to be somewhat more mafic (containing more ferromagnesian silicate minerals) than the granitic rocks comprising the Sierra Nevada.

Gold and Chromite Mineralization: The geologic similarity between the Klamath Mountains and the Mother Lode region of the Sierra Nevada did not escape the notice of prospectors and miners in the mid-1800s. Gold was discovered in placer gravels along the Klamath and Trinity rivers soon after the Gold Rush began. Additional gold deposits were eventually located in ancient river sediments and in the metamorphic basement rocks. Ultimately, the Klamath Mountains became the second largest gold producing region in California.

During and just after World War II, deposits of chromite were extensively mined in the Klamath region. Chromite is an iron chromium oxide mineral ($FeCr_2O_4$) that is the only source of chromium, a valuable metal used in the manufacture

▶ **Figure NC.18** Castle Crags is an exposure of 167-million-year old granite in the Klamath Mountains.



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of specialized steel alloys and in corrosion-resistant steel plating. Chromite is very rare in crustal rocks, but comprises a significant fraction of the upper mantle material. In the Klamath Mountains region, the mantle slices preserved in the Trinity and Josephine ophiolites contained numerous pods of chromite-bearing rock that were rich enough to be mined. Much of the ore was depleted after the 1960s, and production of chromite from the Klamath Mountains has since declined dramatically. For a time, however, the Klamath Mountains was the primary source for this valuable strategic metal.

Section Northern California.3 Summary

- The Klamath Mountains province is a mountainous upland deeply incised by the Klamath River and its tributaries. Several distinct mountain ranges comprise the region, with elevations up to 2,750 meters (9,000 feet). In contrast to the strong northwest orientation of California's major landforms, the ranges in the Klamath Mountains province have a weak north-to-south alignment or a curved trend.
- The bedrock of the Klamath Mountains province has strong similarities with the Sierra Nevada to the south, and can be considered as a northwest continuation of the geologic patterns of the later. In both areas, metamorphic bedrock comprising multiple terranes is intruded by Mesozoic granite plutons and overlain by Cenozoic-age sedimentary and volcanic rocks. The rocks comprising some of the Klamath Mountains terranes are almost identical in type, age, and origin to those of the northern Sierra Nevada. At least a dozen terranes have been identified in the Klamath Mountains, some of which can be assembled into larger superterranes.
- Ophiolites, representing fragments of oceanic lithosphere, are prominent in the terranes of the Klamath Mountains region. The Josephine and Trinity ophiolites are dominated by mafic igneous rocks commonly altered to greenstone and serpentinite.
- Gold and chromite have been mined from the Klamath Mountains region. The gold probably originated in a manner similar to the Mother Lode deposits of the Sierra Nevada. The chromite deposits are concentrated in the mantle rocks present within the Klamath Mountains ophiolite sequences.

Northern California.4
The Great Valley

A Great Depression: Nestled between the Sierra Nevada on the east and coastal mountains to the west, the Great Valley of California is a vast elongated basin extending nearly 700 kilometers (430 miles) and averaging about 80 kilometers (50 miles) wide. The northern portion of the Great Valley is known as the Sacramento Valley, and the southern two thirds is designated as the San Joaquin Valley. These names originate from the two large rivers systems that drain the interior basin from the north and south, respectively. These rivers meet southwest of Sacramento in the Delta region and eventually drain into the San Francisco Bay.

The Sacramento Valley is a remarkably flat interior basin surrounded by elevated terrain to the west (Coastal Ranges), north (Klamath Mountains and Cascade Range), and east (the Sierra Nevada). The Sacramento River system receives runoff from these adjacent highlands via several major tributaries including the Feather, Yuba, American, Pit, and Bear Rivers (Figure NC.19). Because northern California receives significantly more rain than southern California, the Sacramento River is California's largest river, carrying about 18 million acre-feet of water, six times more than the San Joaquin River, toward the sea annually. This water is a critically important resource for agriculture, industry, commerce, and domestic use statewide.

Soils and Agriculture in the Great Valley: The surface of the Sacramento Valley is covered by recent and Pleistocene-age **alluvium** washed into the bottomlands by streams draining the adjacent highlands. These stream sediments consist of a heterogeneous assemblage of channel gravels, river bank sands, silt, and clay deposited on the broad floodplain, and in some places, peat deposits representing plant litter that accumulated in lakes and wetlands. The rivers draining the Sacramento Valley typically follow meandering courses that shift continuously across the

▶ **Figure NC.19** The drainage basin of the Sacramento River.

Map courtesy of the U.S. Geological Survey.

nearly flat floodplain. Over time, the migrating rivers have deposited thick sequences of interlayered river sediments. These alluvial deposits are generally several hundred meters thick, but can be much thicker in the lower areas on the west side of the valley.

The soils developed on the alluvium of the Great Valley are among the most fertile in the world. These soils, coupled with abundant water, mild climate, and a lengthy growing season have made the Great Valley one of the most agriculturally productive regions in North America. The annual value of California agricultural products exceeds $32 billion and most of the products are grown in the Great Valley. In the Sacramento Valley, the principal crops are rice, almonds, walnuts, orchard fruits, grapes, and feed grains. Even before cultivation, the fertility of the Great Valley was noted by early explorers who reported that the Sacramento River flowed through an incredibly lush grassland, with large stands of oaks trees and numerous wetlands.

Soil fertility is the consequence of several inter-related factors, including the texture, chemistry, micro flora and fauna, moisture, and organic content of the soil. However, some vital nutrients can be obtained by plants only from chemicals released during the weathering of mineral grains in the soil. These mineral nutrients include potassium, magnesium, and calcium. The alluvium of the Sacramento Valley is naturally rich in minerals such as feldspar and mica that release these nutrients as they undergo chemical weathering. These mineral grains, in turn, originated primarily in the plutonic rocks and associated metamorphic terranes of the Sierra Nevada and the Klamath Mountains. The agricultural productivity of the Sacramento Valley soils reflects, in part, the vast exposures of these rocks in the upper reaches of the Sacramento River watershed.

Deeper Structure of the Great Valley: Beneath the alluvium and soils at the surface, the bedrock of the Great Valley is comprised of a thick sequence of mostly Mesozoic and Cenozoic sedimentary rocks that are downfolded in a great asymmetrical **syncline** **(Figure NC.20).** These strata are called the Great Valley Sequence, an enormous mass of oceanic sediments exceeding 6,000 meters in maximum

► **Figure NC.20** Generalized diagram of the subsurface structure of the Great Valley, Coast Ranges, and Sierra Nevada.

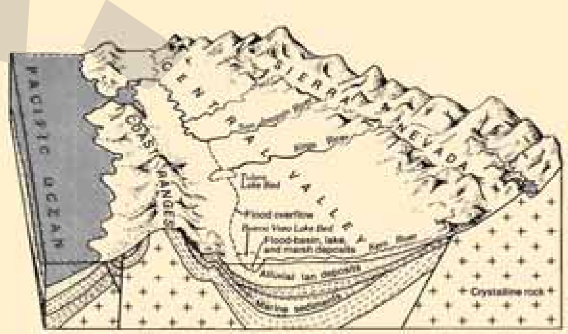


Diagram courtesy of the U.S. Geological Survey.

thickness. Because they are folded downward to depths of 15,000 feet or more, the strata of the Great Valley Sequence are only exposed at the surface in the foothills of the highlands on either side of the valley. To the east, along the Sierra Nevada foothills, the rock layers dip gently toward the center of the valley, although they are steeply upturned to the west, where they are exposed in the foothills of the Coast Ranges (Figure NC.21).

The Great Valley Sequence is comprised mostly of sandstone and shale representing sediment that accumulated in a deep **forearc basin** that developed in the Mesozoic Era. This basin was located between the offshore trench and the ancestral Sierra volcanic arc above the Farallon subduction zone (Figure NC. 22). Much of the sediment eroded from the volcanic and metamorphic rocks in the Klamath and Sierra Nevada regions was transported to the deep seafloor by **turbidity currents**. These great undersea landslides probably were triggered by volcanic eruptions, earthquakes, or storm events along the ancient continental margin. Repeated deposition of sediment by turbidity currents leads to the development of **submarine fans** on the seafloor, and geologists recognize sediment of this type in many portions of the Great Valley Sequence. Some of the sediments in the Great Valley Sequence are rich in organic matter, primarily the remains of microorganisms that continually rained down to the seafloor from the shallow waters above. Over time, this organic matter has become transformed in the subsurface to the combustible hydrocarbons that comprise natural gas. Where these gases are trapped in the porous subsurface sandstones, productive gas wells can be developed. From 1977 to 1998, the annual production of natural gas in the Sacramento Valley region averaged about 100 trillion cubic feet. The majority of this gas originates in the Great Valley Sequence.

Above and Below the Great Valley Sequence: The sediments of the Great Valley Sequence were deposited on top of oceanic lithosphere that can still be recognized by geophysical techniques. The deeply buried oceanic crust in the Great Valley is 7 to 8 kilometers thick and the **moho** beneath is 11 to 16 kilometers below the surface. Surprisingly, this relatively dense oceanic basement appears to be perched above the western extension of the Sierra Nevada batholith. The presence of a thick slab of dense oceanic rock deep beneath the Great Valley may act like a gravitational anchor, helping to explain why this region has remained so low with respect to the surrounding terrain.

The forearc basin in which the Great Valley Sequence accumulated persisted into the early part of the Cenozoic Era. By about 25 million years ago, the rate of subsidence decreased and the basin began to fill in the north. Starting in Late Cenozoic time, the oceans gradually drained away from the Great Valley, and all of the sediments washed into the lowland accumulated in terrestrial environments such as river beds, lakes, and swamps. As we will soon see, volcanoes in the Sierra Nevada and Cascade Range became active at roughly this same time, and some of the erupted material flowed or fell into the Great Valley. Consequently, along the modern periphery of the Great Valley, the Late Cenozoic

▶ **Figure NC.21** Submarine fan deposits of the Great Valley Sequence exposed in the foothills of the Coast Ranges dipping steeply to the east (left).

Frank DeCourten

▶ **Figure NC.22** The Mesozoic forearc basin in which sediments of the Great Valley Sequence accumulated was located between the ancestral Sierra Nevada volcanic arc and oceanic trench related to the Farallon subduction zone.

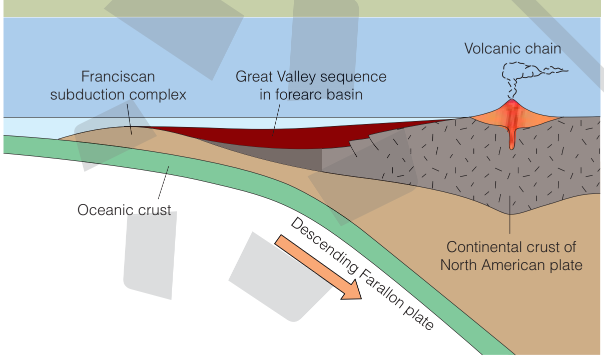
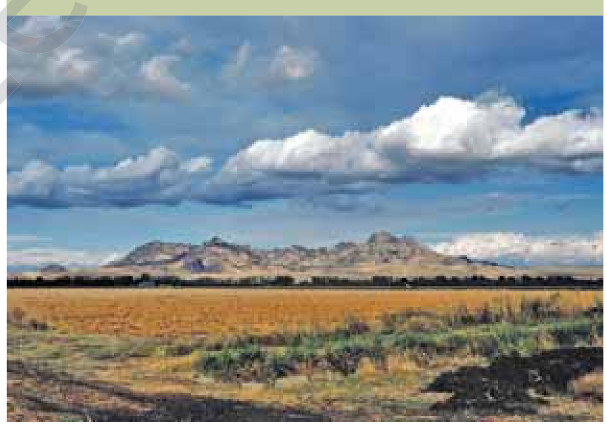


Diagram courtesy of the U.S. Geological Survey.

▶ **Figure NC.23** The Sutter Buttes are the only prominent mountains in the Great Valley of northern California.



Frank DeCourten

rocks are characterized by interlayered volcanic and terrestrial sedimentary rocks.

The Sutter Buttes: About 12 kilometers northwest of Marysville stand the Sutter Buttes, a circular cluster of ragged volcanic peaks, about 17 kilometers (10 miles) in diameter, that rise to an elevation of more than 650 meters (2,100 feet). These peaks are such a striking feature in the monotonously flat interior of the Great Valley that they have attracted attention ever since humans first arrived in northern California (Figure NC.23). The core of the Sutter Buttes consists of several rhyolite domes emplaced as shallow intrusions from 1.6 million to 1.3 million years ago. Surrounding this core is a circular zone of slightly older pyroclastic material of andesitic composition. Geologists

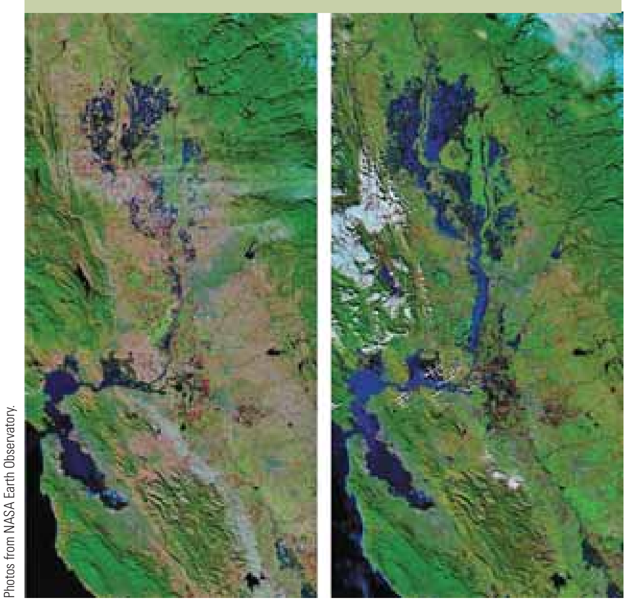
► Figure NC.24 Flowing on a low gradient with an extensive flood plain, the Sacramento River is subject to seasonal flooding that places millions of people at risk.

James S. Monroe

generally consider the Sutter Buttes to be the southernmost expression of volcanic activity related to the Cascade Range to the north. However, development of the Sutter Buttes may also have been influenced by the migration of the Mendocino triple junction. We will review both of these aspects of northern California geology in later sections.

Flooding in the Sacramento Valley: Because it is a nearly flat surface drained by California's largest river (Figure NC.24), the Sacramento Valley is prone to recurring floods (Figure NC.25). The annual flood cycle generally peaks in late winter and early spring as heavy winter rains give way to the melting of the snow pack in the bordering mountains. Before people settled there, the floodplain adjacent to the Sacramento River and its tributaries was repeatedly inundated in a cyclic pattern. The annual floods renewed the floodplain soils and scoured the channel of accumulated sediment and debris.

Today, the intense agricultural and residential development in the Sacramento Valley has resulted in a serious flood hazard for millions of people. Billions of dollars have been invested in flood control measures that include large dams in the foothills, miles of levees, and river bypass channels. Even with these measures, the threat of seasonal floods has not been eliminated from the Sacramento Valley. Attempts to reduce flooding along the Sacramento River have also diminished the beneficial effects of this natural process.



► Figure NC.25 Flooding in the Sacramento Valley, 2005–2006. Photo on the left was taken from space on Dec. 10, 2005 immediately prior to heavy late winter rains. Photo on the left is from Jan. 4, 2006. Note that the Sutter Buttes were entirely circled by flood waters from the Sacramento River.

Photos from NASA Earth Observatory.

Section Northern California.4 Summary

- The Great Valley is an elongated lowland situated between the Sierra Nevada on the east and the Coast Ranges on the west. The northern portion of the Great Valley is referred to as the Sacramento Valley, named for the large south-flowing river system that drains it. The watershed for the Sacramento River includes the highlands of the northern Sierra Nevada, Cascade Range, Klamath Mountains, and the northern Coast Ranges. Because these mountainous regions receive more precipitation than other regions of the state, the Sacramento is California's largest river.

- Great quantities of alluvium have been deposited across the floor of the Great Valley by rivers draining the adjacent highlands. The fertility of the soils of the Great Valley reflects, in part, the concentration of vital mineral nutrients derived from the weathering of rocks in the adjacent watersheds. The natural fertility of the Great Valley soils, coupled with the prevailing climate and abundance of water, has made the Great Valley one of the most productive agricultural regions in the world.

- In the subsurface of the Great Valley, Mesozoic and Cenozoic sedimentary rocks of the Great Valley Sequence are downfolded in the form of a large syncline. The Great Valley Sequence sediments accumulated in a deep forearc basin associated with the Farallon subduction zone. Most of the sandstone and shale in these rocks was transported to the deep ocean floor by turbidity currents and accumulated as submarine fans. Organic matter in parts of the Great Valley Sequence has produced significant quantities of natural gas.

- The Great Valley Sequence accumulated on dense oceanic lithosphere that lies deep under the Great Valley. This dense slab of rock is thought to be related to the low elevation of the region in relation to the surrounding highlands.

- The Sutter Buttes are a distinctive cluster of volcanic domes that erupted in the Sacramento Valley 1.6 million to 1.3 million years ago. The magma that surfaced in this location may be related to the Cascade Range volcanoes to the north or to the migration of the Mendocino triple junction along the coast.

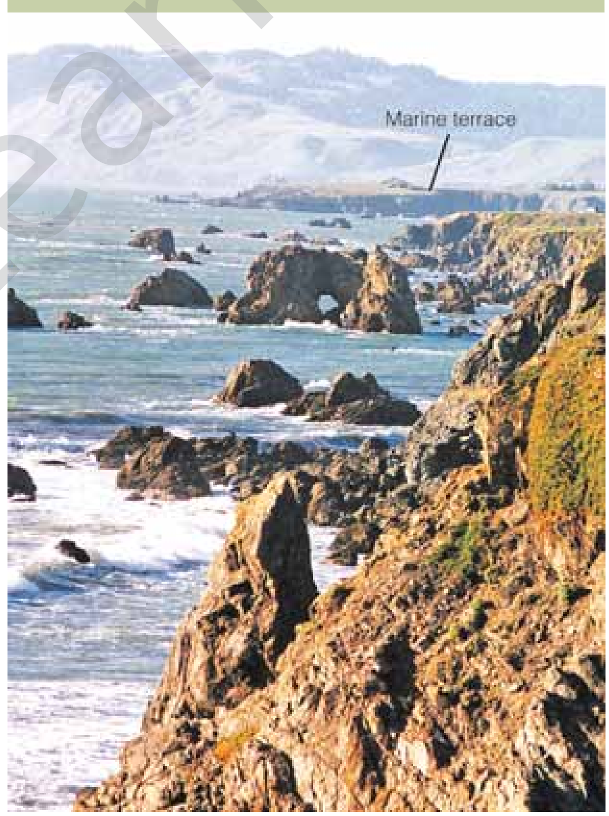
- Because it is a nearly flat valley drained by California's largest river, the Sacramento Valley is naturally prone to cyclic flooding. Over geologic time, the recurring floods that inundated the floodplain have added alluvium to the valley surface and renewed soil components. Flood control measures, such as levees and upstream dams, are necessary to protect floodplain communities and industries, but they also limit the beneficial effects of the annual flood cycles.

Northern California.5
The Northern Coast Ranges

The rugged north coast of California is one of the most scenic seashores in the world. In most places along this rocky coast, beaches are narrow and sea cliffs rise from the water's edge to elevations of several thousand meters in just a few kilometers. Spectacular examples of coastal landforms such as **sea stacks, sea arches**, and **marine terraces** (Figure NC.26) provide evidence of recent emergence of the northern California Coast. The vigorous erosion that accompanies such an actively rising coast is responsible for the spectacular ruggedness of the Northern California seaside.

The relatively young coastal mountains of California define the Coast Ranges physiographic province that extends more than 600 kilometers (960 miles) from the Transverse Ranges in the south to the Oregon border, and beyond. Within this region, coastal mountains such as the Santa Cruz Mountains, the Mendocino Range, the Gabilan Range, and the Diablo Ranges of northern California are all aligned in a consistent northwest trend. The Coast Ranges are generally oriented parallel to the Great Valley and Sierra Nevada provinces to the east, and have a similar extent. This suggests that the geologic evolution of these regions may be linked to

► **Figure NC.26** Steep cliffs, sea stacks, and sea arches characterize northern California's emergent coast.



Sue Monroe

▶ Figure NC.27 Chert of the Franciscan complex exposed in Marin County. Most of the layers are 5 cm thick.

Sue Monroe

some of the same tectonic events. However, the recent emergence of the Coast Ranges was strongly affected by the evolution of the San Andreas fault system and the development of the modern transform boundary between the Pacific and North American plates. Thus, though the older bedrock of the Coast Ranges can be related to broader tectonic patterns, the story of their more recent emergence involves plate tectonic events that affected only the coastal region.

The California Coast Ranges have traditionally been divided into northern and southern portions, with San Francisco Bay arbitrarily dividing the two. However, for sound geologic reasons, it is more meaningful to divide the Coast Ranges into northern and southern portions separated by the San Andreas fault system. This great fault zone slices diagonally across the Coast Range, and the areas on opposite sides have unique and distinctive geologic histories. By this definition, the northern Coast Ranges extend northward from approximately Monterey Bay and the Gabilan Range to the Oregon border. It is this part of the larger Coast Ranges province that we will refer to as the North Coast Ranges, and on which we will focus in the following sections.

The Chaotic Franciscan Complex: In most of the Northern Coast Ranges, the basement rock consist of an incredibly complex assemblage of intensely deformed and metamorphosed sandstone, shale, chert, basalt, and plutonic rocks. In many exposures of these rocks, layering and other internal structures have been obliterated by internal movements such that some geologists have described it as a "churned" rock assemblage. In the early 1900s, the name Franciscan was applied to these mangled rocks for their prevalence in the San Francisco Bay region. Since then, the Franciscan rocks have become one of the most famous and well studied rock units in the world. For decades the complexities of the Franciscan assemblage defied geologic explanation. With the advent of the plate tectonic paradigm in the 1970s, geologists began to unscramble the origin of this chaotic rock sequence. Today, there is general agreement that the Franciscan rocks represent a subduction complex, a mixture of rocks that form in association with subducting oceanic lithosphere.

The age of rocks comprising the Franciscan complex ranges from about 200 million to 80 million years. Recall that about 140 million years ago, the Farallon plate began to subduct beneath western North America, generating the magma that ultimately formed the granite batholith of the Sierra Nevada (see Figure NC.22).Offshore of that ancient continental margin, a deep trench developed on the oceanic floor. In this trench, sand and rock fragments were washed from the continent and accumulated in great thickness. Such sediments comprise **graywacke**, an impure sandstone that is the most common rock type in the Franciscan assemblage. The Franciscan graywacke deposits commonly exhibit **graded bedding**, suggesting that turbidity currents transported them into the deep basin. Other deep ocean sedimentary rocks in the Franciscan complex also include fine-grained shale and chert (Figure NC.27). In addition to the sedimentary components of the Franciscan rocks, mafic igneous rocks such as pillow basalt, gabbro, and peridotite are present. The igneous materials probably comprised portions of the Farallon plate that originated at ancient spreading ridges, as submarine lava flows, or in the upper part of the mantle. As the Farallon plate collided with North America, and was forced downward, the igneous rocks were subjected to high temperatures, extreme pressures, and chemically active fluids including hot seawater. Alteration of the iron and magnesium-bearing silicates in the igneous components of the Farallon plate produced such minerals as chlorite, pumpellyite, antigorite, chrysotile (asbestos), and lizardite. These greenish-colored minerals are abundant in greenstone and serpentinite (Figure NC.28), both of which are common in the Franciscan complex. Serpentinite plays an important role in creating the "churned" appearance of the Franciscan complex. It is significantly less dense than the igneous rocks from which it develops. Under the temperature and pressure conditions that prevail in subduction zones, serpentinite can become mobile and plastic, squeezing upward into the overlying rocks to disrupt the original layering.

The internal structure of the Franciscan rocks is so complex that it bewildered geologists for decades. The original layers of the sedimentary rocks are highly deformed (Figure NC.29) or even completely obliterated by serpentinite intrusion and tectonic deformation. The igneous rocks are usually metamorphosed, fragmented, and broken into isolated blocks. The entire rock assemblage is further complicated my numerous faults and shear zones that separate the sequences into discontinuous blocks. Such a mixture of deformed, jumbled, and altered rocks is known as a mélange, a French term for a mixture of different components. The origin of these rocks was a mystery to geologists until the plate tectonic theory provided a new model for interpreting the complexity of the Franciscan assemblage.

The Franciscan rocks, as a whole, are now thought to be a subduction complex, a heterogeneous mass of deformed and altered rocks that forms in and near subduction zones. The sedimentary components of the Franciscan complex

► **Figure NC.28** Serpentinite, like this sample from the northern Coast Ranges, is California's official State Rock.

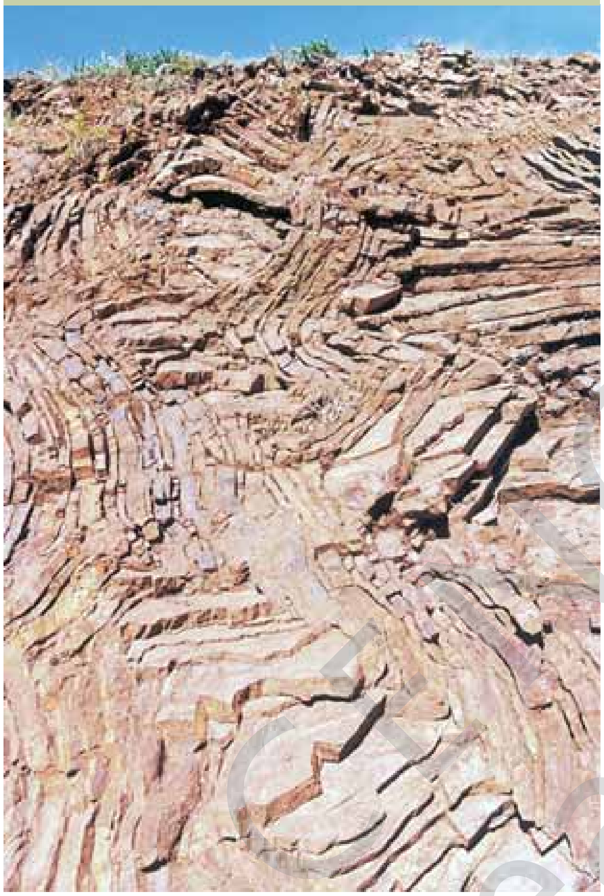
Frank DeCourten

represent sand, silt, and ooze that accumulated in the trench or on the Farallon plate as it approached North America during the Mesozoic Era. Some of these sediments were scraped off the plate as it descended beneath the leading edge of North America and deformed by the immense pressure generated in the zone of plate convergence. Some sedimentary rocks were also pulled downward by the descending Farallon plate to depths of 15 kilometers or so beneath the surface. In this high-pressure and low-temperature environment, **blueschist** was produced, a metamorphic rock rich in the bluish mineral glaucophane. The igneous components of the Farallon plate descended to even greater depths and encountered higher temperature conditions where the serpentintite and greesnstone formed. Slices of rock were sometimes broken from the descending slab and thrust over or crushed against the edge of the continent. In addition, the Farallon plate was evidently carrying isolated seamounts, lava plateaus, and coral reefs that became detached and embedded into the Franciscan mélange. Geologists currently recognize no fewer than nine such micro-terranes in the Franciscan Complex in the San Francisco Bay region. The chaotic nature of the Franciscan complex thus reflects the diversity of rocks types, the varying degrees of metamorphism, the accretion of exotic terranes, and the intensity of deformation that result from plate subduction.

The subduction of the Farallon plate persisted under the northern Coast Ranges for more than 130 million years, extending well into the Cenozoic Era. During this time, a thick wedge of Franciscan rocks developed along the leading edge of North America, but the coastal mountain ranges had not been elevated from the seafloor. About 30 million years ago, the plate boundary along the west coast began to shift from a convergent type to a **transform** boundary. The emergence of the modern Coast Ranges is linked to development of the modern transform boundary between the Pacific and North American plates.

Evolution of the San Andreas System: Recall that the Farallon plate originated at an offshore spreading ridge that separated it from the Pacific plate moving to the west (see Figure NC.3). Segments of this spreading ridge were offset by transform faults to create an irregular divergent boundary. Through the Mesozoic and Early Cenozoic Eras, the North American plate was moving faster to the west than was the Farallon plate to the east. Consequently, the west edge of North America eventually collided with the spreading ridge as the intervening Farallon plate was consumed by subduction. This collision first occurred at the approximate latitude of modern Los Angeles about 30 million years ago (Figure NC.30). One consequence of this collision was the creation of a point where three plates—the Farallon, Pacific,

▶ **Figure NC.29** Deformed chert in the Marin Headlands terrane of the Franciscan complex.



James S. Monroe

▶ **Figure NC.30** Evolution of the San Andreas fault system as a transform boundary between the Pacific and North America Plates. The Juan de Fuca Plate north of the Mendocine Triple Junction is a remnant of the Farallon plate.

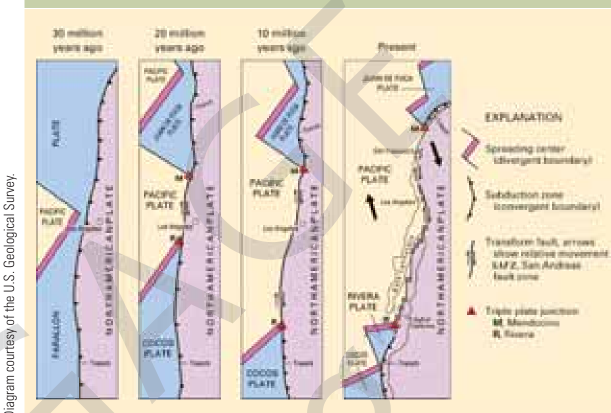


Diagram courtesy of the U.S. Geological Survey.

▶ **Figure NC.31** Major Fault of California, including the San Andreas and related stike-slip faults that represent the boundary between the Pacific and North American plates.

Map courtesy of the U.S. Geological Survey.

and North American—met. Such points are called **triple junctions**, and they signify places where different kinds of plate boundaries exist in proximity to each other.

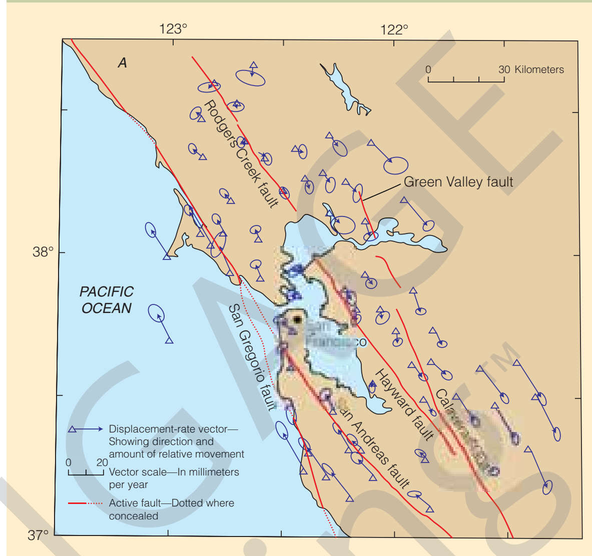
After the initial triple junction developed, the North American plate continued to overrun more of the spreading ridge. This caused the original triple junction between the Farallon, Pacific, and North American plates to separate into two (see Figure NC.30). The continued westward motion of the North American plate caused the two triple junctions to migrate in opposite directions along the continental margin. The northern triple junction migrated through the San Francisco Bay area about 10 million years ago. Today, the Mendocino triple junction is located near Cape Mendocino, more than 200 kilometers (130 miles) north of San Francisco. The corresponding point to the south is the Rivera triple junction, located near the southern tip of Baja California.

The collision between the spreading ridge and the North American continent brought the Pacific plate into contact with the North America plate. Because both plates had westerly motions, this new boundary ended the long era of plate convergence and subduction. Instead, differences in the rates and directions of plate motion gave rise to a **transform** plate boundary, in which the two plates slide laterally past each other. The development of the transform boundary between the North America and Pacific plate initiated the famous San Andreas fault system (Figure NC.31). The San Andreas fault is perhaps the best known fault in the world, but it is only one of hundreds of faults in the zone that bears the same name. Collectively, these faults accommodate the relative motion between the North American and Pacific plates through **right-lateral strike-slip** displacement (Figure NC.32). It is important to understand that the San

▶ **Figure NC.32** The right-lateral displacement on the San Andreas Fault is illustrated by the offet of this stream channel in the southern Coast Ranges. View is to the west from the North American plate (foreground) to the Pacific plate (distance).

John S. Shelton

▶ **Figure NC.33** Major faults in the San Francisco Bay area. The blue arrows represent their average displacement rates.



Map courtesy of the U.S. Geological Survey

▶ **Figure NC.34** Granite of the Salinian Block with dark-colored xenoliths at Point Reyes National Seashore. This granite is very similar to the plutonic core of the Sierra Nevada,

Dick Hilton

Andreas fault system is actually a zone of dominantly strike-slip faults that ranges from 100 kilometers to nearly 300 kilometers wide. The collective motion of these faults allows the Pacific plate to slip to the northwest relative to the North American plate at an average rate of about 5 centimeters (2 inches) per year. This may sound very small, but it is enough to displace older geologic features by more than 300 kilometers (185 miles) since the transform boundary originated.

In the San Francisco Bay area, the San Andreas fault is one of several large right-lateral faults that comprise the plate boundary (Figure NC.33). Other major faults in this region include the Calaveras, Hayward, and San Gregorio faults that are nearly, but not exactly, parallel to the plate boundary. The San Andreas fault extends offshore from Point Arena to the Mendocino triple junction. The San Andreas fault zone produces continuous earthquakes, some of which pose serious threats to California residents. We will examine the pattern of seismic activity along the San Andreas in a later section.

The Salinian Block—An Immigrant from the South: In the northern Coast Ranges, rocks of the Franciscan complex are absent west of the San Andreas fault. In places such as Point Reyes National Seashore, the basement rocks consist of Mesozoic-age plutonic and metamorphic rocks overlain by Cenozoic-age sediments (Figure NC.34). These rocks comprise a block that can be traced south from Point Arena to the southern Coast Ranges. Because such materials are especially prominent around the Salinas Valley, geologists refer to this mass as the Salinian block (Figure NC.35).

► **Figure NC.35** Right lateral displacement along the San Andreas Fault has moved the Salinian Block more than 500 kilometers to the northwest.

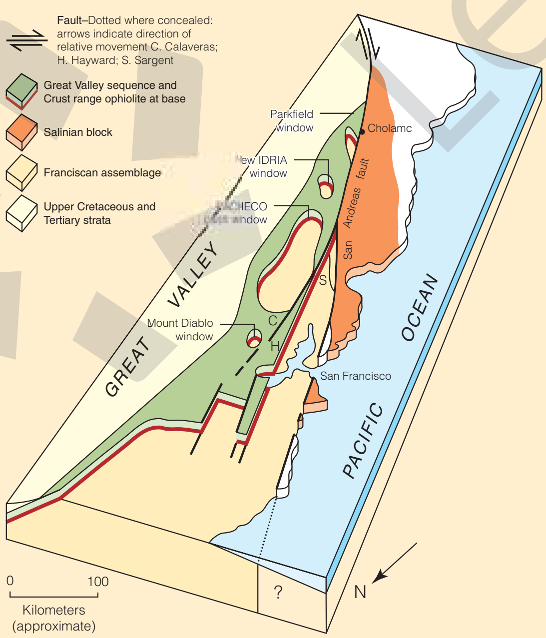


Diagram courtesy of the U.S. Geological Survey.

The granites of the Salinian block are 78 million to 110 million years old, and are remarkably similar in age and composition to the granites of the southern Sierra Nevada. In addition, metamorphic rocks associated with the granite basement of the Salinian block are almost identical to the roof pendants of the Sierra Nevada. These similarities suggest that the Salinian block was part of the Sierra Nevada batholith before the development of the San Andreas fault system. The Salinian block has since been transported a minimum of 550 kilometers (340 miles) to the northwest by right-lateral displacement along this fault.

The Rise of the Northern Coast Ranges: Overlying the basement rocks of both the Salinian block and the Franciscan complex are as much as 6,000 meters (nearly 20,000 feet) of Cenozoic-age sedimentary rock that records the emergence of the modern Coast Ranges. This sedimentary record is complicated by motion along the San Andreas system, but it is clear that there were several different basins where oceanic and terrestrial sediments accumulated. The older deposits in these basins are mostly mud, ooze, and sand that settled out on the continental shelf. Some sequences, such as the Monterey Formation (Miocene Epoch; 11 million to 22 million years old), accumulated in deep water, where organic material became concentrated in the mud and ooze (Figure NC.36). The Monterey Formation is believed to be the source rock of much of California's petroleum.

By Late Pliocene time, 3 million to 4 million years ago, the coastal basins were receiving mostly terrestrial sediments, indicating that the northern Coast Ranges were rising from the seafloor during this time. However, the complex association of Late Cenozoic river, estuary, and beach deposits in the northern Coast Ranges indicates that the precise timing and rate of uplift was somewhat variable. Accompanying the uplift of the modern northern Coast Ranges was the eruption of volcanic ash and lava in the areas around Sonoma (3 million to 8 million years ago) and Clear Lake (2 million to 10,000 years ago). Ash from these eruptions is commonly found within the layers of Late Cenozoic sedimentary rocks. This relatively recent volcanic activity in the northern Coast Range is probably related to the northward migration of the Mendocino triple junction. In the Clear Lake volcanic region, shallow residual magma is probably responsible for the steam that has produced as much as 2,000 megawatts of electricity annually at The Geysers geothermal field.

The forces that raised the north Coast Ranges in Late Cenozoic time are continuing to elevate the region. The general northwest alignment of mountain ranges and drainages is attributable to the orientation of the strike-slip faults that influenced the Late Cenozoic uplift. Several of the mountain ranges are still being squeezed upward by compression generated by small differences in the alignment of active faults. The coastal mountains of northern California have only recently emerged as land, and they will grow even higher as the Pacific plate continues to slide past the North American plate.

▶ **Figure NC.36** Folded layers of the Monterey Formation in the Monterey Peninsula area of the northern Coast Ranges.

Dick Hilton

Section Northern California.5 Summary

- The northern Coast Ranges include mountains such as the Mendocino Range, the Santa Cruz Mountains, and the Diablo Range that are aligned parallel to the Great Valley and Sierra Nevada. These are relatively young mountain ranges, and their continuing uplift is related to the emergence of the northern coast.
- The bedrock of the northern Coast Ranges is dominated by the Mesozoic-age Franciscan complex, an incredibly varied mixture of sedimentary and metamorphic rocks known as a mélange. The Franciscan complex accumulated in or adjacent to the Farallon subduction, and includes several exotic terranes that originated far from northern California.
- The San Andreas fault zone cuts diagonally across the northern Coast Ranges and is part of the modern transform boundary between the Pacific and North American plates. This boundary evolved when North America collided with and overran the Farallon-Pacific plate spreading center, beginning about 30 million years ago. Right-lateral strike slip motion on the San Andreas and other faults helps to accommodate the northwest motion of the Pacific plate relative to the North American plate.The Salinian block is a large fragment of crust in the northern Coast Ranges that has been transported at least 550 kilometers to the northwest by right-lateral displacement along the San Andreas fault zone.
- The mountains of the northern Coast Ranges are all relatively young, with uplift beginning only 3 million to 4 million years ago. The rise of the Coast Ranges is documented by the shift from marine to terrestrial sediments in Late Pliocene time. The forces that lifted the Coast Ranges appear to be related to the interaction of blocks separated by various faults within the San Andreas fault system and to the northward migration of the Mendocino triple junction.

Northern California.6 Volcanoes of the Cascade Range and the Modoc Plateau

The landscape of northeastern California is dominated by the Cascade Range and the adjacent Modoc Plateau (see Figure NC.1), which together create a scenic volcanic wonderland in this part of the state. The Cascade Range includes majestic Mount Shasta (4,319 meters/14,161 feet high; Figure NC.37), Mount Lassen (3,188 meters/10,457 feet high), and scores of other smaller volcanoes of all types. The Modoc Plateau is a high lava plain east of the bordering Cascades averaging about 1,350 meters (4,500 feet) in elevation (Figure NC.38). Many volcanoes are perched on this arid plateau, but the largest of them is the Medicine Lake volcano (Figure NC.39) near the eastern margin of Cascade Range. This immense shield volcano rises to an elevation of 2,375 meters (7,795 feet) and covers more than 2,000 square kilometers (770 square miles).

Both the Modoc Plateau and the Cascade Range in northern California represent only a portion of larger geologic provinces that extend into adjacent states. The Cascade Range extends northward from the southern terminus at Mount Lassen for more than 800 kilometers (500 miles) into southern British Columbia. Other prominent Cascade volcanoes include Oregon's Crater Lake, Mount Baker, and Mount Hood, along with Mount Rainier and Mount St. Helens of Washington. The Modoc Plateau is likewise continuous with the Columbia Plateau of Oregon, Washington, and Idaho. The Modoc Plateau encompasses nearly 26,000 square kilometers; the Columbia Plateau is roughly 20 times larger.

The principle volcanic features of the Cascade Range and Modoc Plateau are all relatively young, generally resulting from eruptions that occurred during the past 3 million years (Figure NC.40). Earlier Cenozoic-age volcanic activity did occur in the region, but the structures built during this time have either been eroded or obscured beneath the younger lava flows. The most recent activity

► **Figure NC.37** Mt. Shasta is the second highest composite in the Cascade Range and measures about 20 km in diameter at the base.

Diagram courtesy of the U.S. Geological Survey.

Figure NC.38 Crater Mountain in Lassen County is one of several young shield volcanoes that erupted the basaltic lava in the Modoc Plateau region.

James S. Monroe

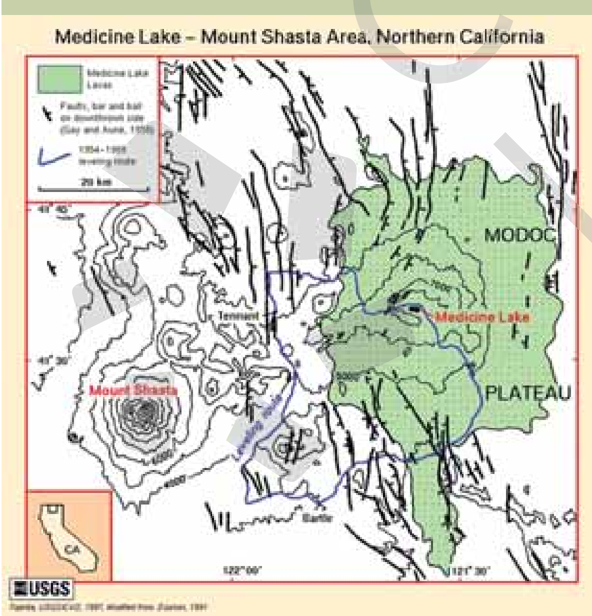


Figure NC.39 Map showing location of Mt. Shasta and the Medicine Lake shield volcano, 60 kilometers to the east.

Map courtesy of the U.S. Geological Survey.

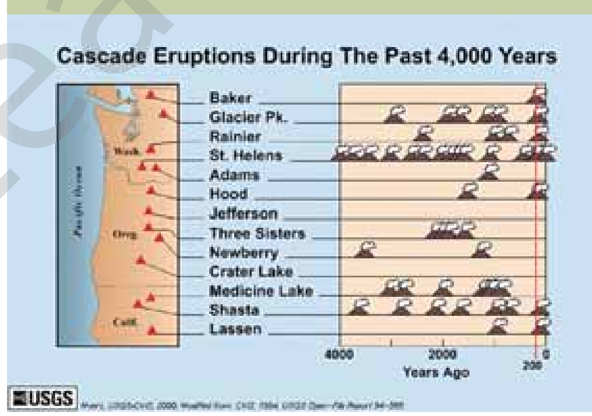


Figure NC.40 Recent eruptions of the volcanoes of the Cascades Range. Note that Mt. Shasta and Mt. Lassen in California have both been active in the past several centuries.

Map courtesy of the U.S. Geological Survey Cascade Volcano Observatory.

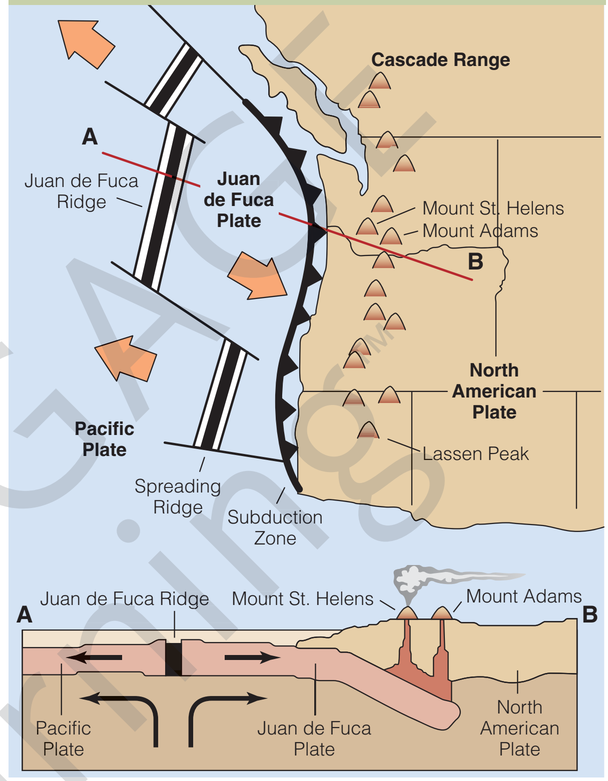
occurred in the years 1914 to 1917, when Mount Lassen experienced a series of small summit eruptions (Figure NC.41). The recent volcanic activity in the Cascade Range and Modoc Plateau is related to the plate convergence that exists along the margin of North America, north of the Mendocino triple junction. Here, oceanic plates are descending beneath the continent in the Cascadia subduction zone, in the process generating magma that continues to rise into the Cascade region.

The Cascadia Subduction Zone: The Cascadia subduction zone extends for 1,200 kilometers (750 miles) along the west edge of North America from southern British Columbia to northern California (Figure NC.42). Along this convergent plate boundary, the Juan de Fuca plate (and

▶ **Figure NC.41** A summit eruption from Mt. Lassen in 1915.

Diagram courtesy of the U.S. Geological Survey.

▶ **Figure NC.42** Plate tectonic setting of the Pacific Northwest. Subduction of Juan De Fuca plate beneath North America accounts for the volcanism of the Cascade Range.



its southernmost segment, the Gorda plate) is moving under the advancing continent at a rate of 3 to 4 centimeters per year. Water released from the sinking slab causes subsurface rock to melt, forming magma bodies beneath the Cascade Range. Magma produced in this way is dominantly andesitic in composition and commonly contains large amounts of dissolved gases such as water vapor, carbon dioxide, and sulfurous vapors. The larger volcanoes in the Cascade chain are **composite** cones built through a series of explosive eruptions, such as the 1980 eruption of Mount St. Helens, alternating with less violent effusions of viscous magma.

The Cascadia subduction zone is terminated to the south by the Mendocino fracture zone, a transform fault that separates the Juan de Fuca (Gorda) plate from the Pacific plate (see Figure NC.42). Because there is no plate convergence south of the Mendocino fracture zone, no subduction-related volcanic activity occurs in that part of California. Mount Lassen, at the southern end of the Cascade Range, is located just slightly north of the landward projection of the Mendocino fracture zone.

California's Cascade Volcanoes: Among the hundreds of volcanoes in the California portion of the Cascade Range, three merit special attention because of their size and potential for future activity. Though future eruptions could occur almost anywhere in the region, Mount Shasta, Medicine Lake, and Mount Lassen volcanoes appear to have been the most active over the past several centuries. Each of these volcanic centers has a unique history, and poses distinctive threats to residents and visitors.

Mount Shasta (see Figure NC.37) is one of the largest **composite volcanoes** in the Cascade chain. This volcano was constructed over the past 100,000 years by hundreds of eruptions, including at least 13 in the past 10,000 years. These eruptions produced andesitic lava flows, pyroclastic flows, and debris flows, some of which extended well beyond the base of the volcano. Shastina, a small volcanic cone on the western flank of Mount Shasta (Figure NC.43), resulted from eruptions that occurred between about 9,300 and

▶ **Figure NC.43** Mt. Shasta and Shastina, seen from the north

Lyn Topinka/USGS

9,700 years ago. The most recent activity at Mount Shasta was about 200 years ago, when several small debris flows, possibly triggered by steam eruptions, originated from the summit region.

At Medicine Lake, eruptions began about 700,000 years ago, when great volumes of basalt lava flowed onto the surface, building the base of this large shield volcano (Figure NC.44). The eruption of voluminous basalt flows is generally associated with divergent plate boundaries or **hot spots**, and is unusual in subduction-related volcanic areas. The basalt eruption at Medicine Lake is probably related to the proximity of the region to the Basin and Range province immediately to the east. In this area, the early stages of continental rifting may be in progress as a new divergent boundary develops in Nevada. Perched atop or along the gently sloping flanks of the Medicine Lake volcano are numerous **cinder cones** that provide sources for decorative rock, concrete aggregate, and roadbed material. The more recent eruptions at Medicine Lake, some probably less than 100 years old, have produced silica-rich magma that resulted in obsidian flows and rhyolite domes on the higher slopes.

▶ **Figure NC.44** Basalt Flow and Cinder Cone in the Medicine Lake Highland of Northern California.

Rick Hazlett

▶ **Figure NC.45** Mt. Lassen, the southern most peak in the Cascade Range.

Sue Monroe

Mount Lassen (Figure NC.45) is unusual with respect to the other volcanoes of the Cascade Range in that it is not a composite volcano. Rather, it is a **lava dome** volcano, a bulbous steep-sided structure formed by viscous magma above a volcanic conduit. The rock comprising the lava dome at Mount Lassen is mostly **dacite**, representing sticky silica-rich magma that oozed up the conduit a little more than 11,000 years ago. Before the development of the Mount Lassen lava dome, a much larger composite volcano existed to the west. Geologists have named this ancient volcano Mount Tehama (Figure NC.46), and it was the site of numerous violent volcanic blasts over the past 600,000 years. Mount Lassen is the only California volcano to be observed erupting in historic time. Between 1914 and 1921, a series of small eruptions, mostly producing ash and steam, occurred near the summit of the lava dome. In May of 1915, however, somewhat larger eruptions sent glowing avalanches of debris down the flanks of Mount Lassen, and produced a small dacite lava flow on the. Today, visitors to Lassen Volcanic National Park can explore hot springs, boiling mud pots, and gas-discharging **fumeroles** that provide hints that the volcanic system is still active.

Volcanic Hazards in Northern California: All of the volcanoes of the Cascade Range and Modoc Plateau region are geologically young, and it is almost certain that there will be future eruptions in the region. In addition, the presence of magma at shallow depths may be responsible for the geothermal activity around Clear Lake in the northern Coast Ranges. Though these areas are distant from large population centers, future eruptions could produce widespread impacts, adversely affecting distant communities as well as local residents and visitors. A major volcanic eruption in the Cascade Range or elsewhere in northern California could also affect agriculture, transportation, communications, water quality, timber resources, and recreation over a broad area.

Volcanic eruptions can threaten human welfare by generating destructive flows of lava or debris, by filling the skies with clouds of ash and other fine rock particles, and by emitting noxious gases such as carbon dioxide, chlorine, or acidic

► **Figure NC.46** The original profile of Mt. Tehama near the lava dome of Lassen Peak.

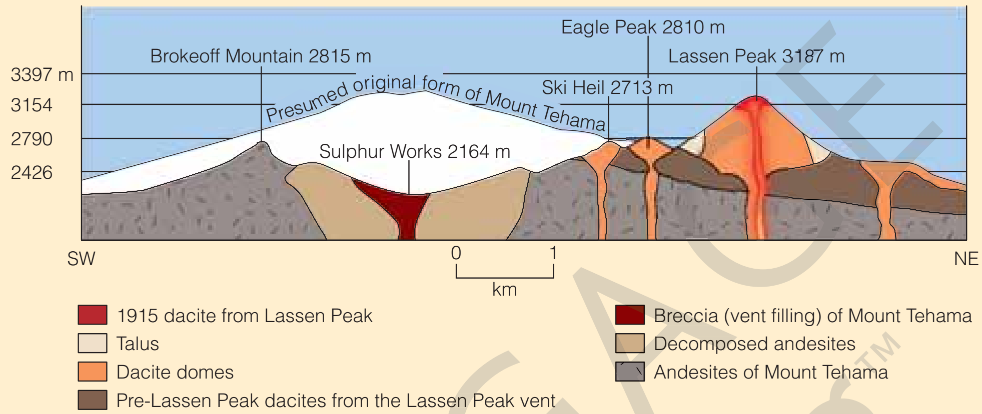
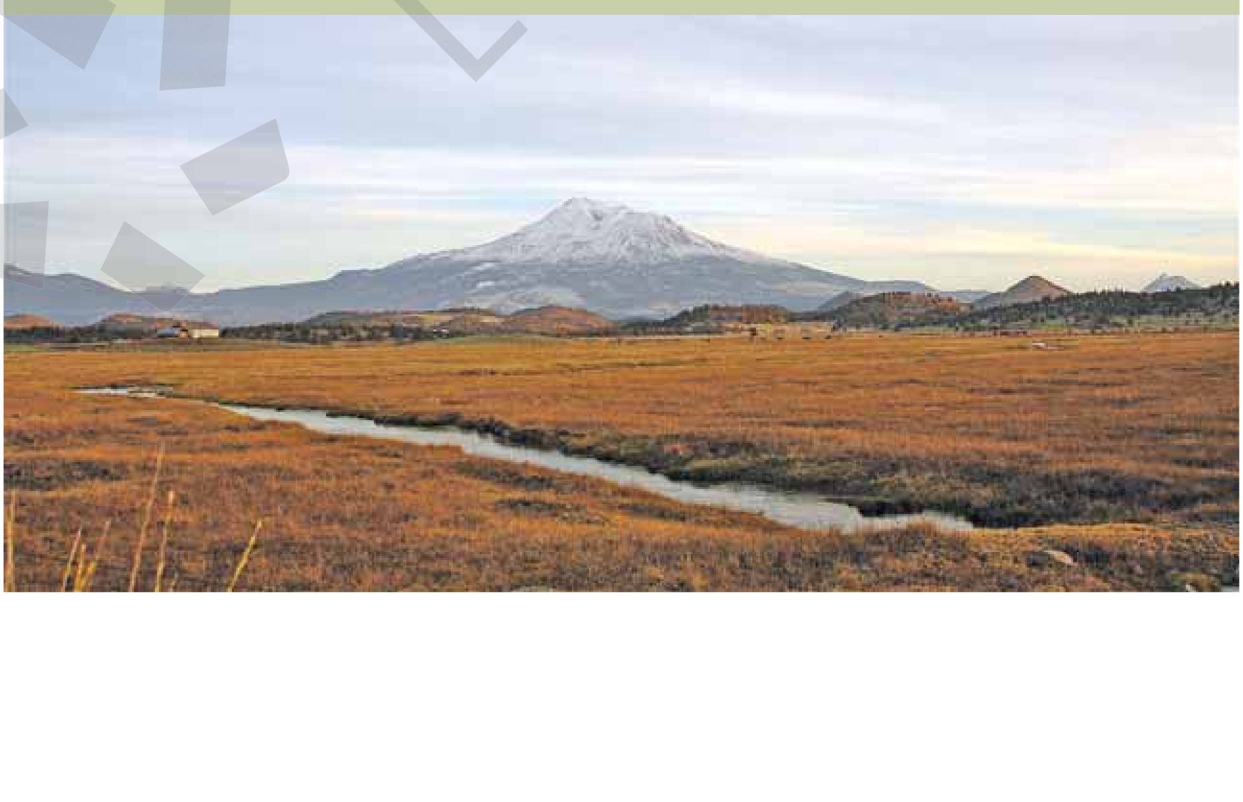


Diagram courtesy of the U.S. Geological Survey.

compounds. Of these multiple potential hazards, large flows of pyroclastic material from Cascade volcanoes would be the greatest threat in northern California. The geologic evidence indicates that between 300,000 and 360,000 years ago, an explosive eruption at Mount Shasta produced a volcanic debris flow that traveled 45 kilometers from the volcano and buried an area exceeding 450 square kilometers in rubble (Figure NC.47). Even larger volcanic mudflows, known as lahars, resulted from prehistoric eruptions at both Mount Lassen and Mount Shasta. And during the relatively small eruptions of 1915, ash particles from Mount Lassen fell as far away as Elko, Nevada, 500 kilometers (300 miles) to the east.

Mindful of the serious implications a large eruption in northern California would have, geologists have prepared volcanic hazard maps of the most sensitive areas and have helped develop evacuation plans for disaster response agencies. In addition, both Mount Shasta and Mount Lassen (along with other areas in central and southern California) are continuously monitored by scientists from the U.S. Geological Survey for signs of renewed activity. In the absence of any means to accurately predict future volcanic eruptions, the combination of hazard assessments beforehand, strategic preparedness, and monitoring will help limit the harmful consequences of future eruptions.

► **Figure NC.47** The hummocky terrain in the foreground was produced by an avalanche of volcanic debris from Mt. Shasta more than 300,000 years ago.



Dick Hilton

Section Northern California.6 Summary

- The Cascade Range of northern California is part of a chain of mostly composite volcanoes that extends north into British Columbia. This chain includes the famous volcanoes of the Pacific Northwest including Mount Rainier, Mount St. Helens, Mount Hood, and Crater Lake. In northern California, Mount Lassen and Mount Shasta are the most prominent volcanoes of the Cascade Range. The Modoc Plateau to the east is a high volcanic table land with numerous shield volcanoes, such as that in the Medicine Lake highland, and cinder cones.
- The magma that sustains the volcanic activity in the Cascade Range arises from the Cascadia subduction zone, in which the Juan de Fuca plate descends beneath North America. Water released from the subducting plate induces the formation of magma bodies more than 100 kilometers beneath the surface. This magma is generally intermediate to felsic in composition, relatively viscous, and laden with magmatic gases. These factors commonly lead to explosive eruptions and the construction of composite volcanoes in the Cascade Range.
- Mount Shasta is a large composite volcano built in a series of eruptions over the past 100,000 years. Mount Lassen is a lava dome volcano that was last active in the early 1900s. The Medicine Lake highland is a large shield volcano, with smaller cinder cones and obsidian flows on its flanks and summit. The most recent eruptions in the Medicine Lake region may have occurred only 100 years ago. All of these volcanoes are potential sites of future eruptions in northern California.
- Because they all have the potential for future activity, the Cascade Range volcanic centers pose serious volcanic hazards for people in northern California. The geologic record of previous eruptions demonstrates that the Cascade volcanoes can produce pyroclatic flows, volcanic mudflows known as lahars, and ash falls that could affect communities hundreds of kilometers away. These threats can be mitigated by continuous monitoring of the volcanic areas, assessment of the potential hazards beforehand, and preparations for responses to the future eruptions.

Northern California.7
The Basin and Range of Northeast California

East of the Modoc Plateau in extreme northeastern California, the volcanic table land is broken by numerous large normal faults into a series of elevated blocks and lower basins. Principal among these mountains and valleys are the Warner Range, rising to 3,017 meters (9,892 feet), and Surprise Valley, lying 1,600 meters (5,200 feet) lower immediately to the east. The displacement between the Warner Range and Surprise Valley is a result of the motion along normal faults along the base of the steep eastern escarpment of the mountain block. These faults comprise the Surprise Valley fault zone, which has a total cumulative of more than 14,000 feet. Normal faulting in this area began as early as 14 million years ago, but much of the displacement has occurred in more recent times. The Honey Lake basin to the south of Surprise Valley is also a depression bounded by normal faults.

The pattern of alternating high mountains and intervening basins in these small areas of northern California continues eastward for hundreds of kilometers into Nevada and portions of the adjacent states. This corrugated landscape, covering more than 770,000 square kilometers (300,000 square miles) of western North America is known as the Basin and Range province. In this immense region, tensional forces are stretching the Earth's crust and fracturing it into blocks bounded by normal faults. The hanging walls of the normal faults move downward to form the basins or **grabens**, while the mountain blocks remain high to form **horsts**. Surprise Valley and the Honey Lake basin are only two of hundreds of depressions formed as the crust in the Basin and Range province yields to tensional stresses.

Geology and Geothermal Resources of the Warner Range region: The bedrock of the Warner Range consists mostly of volcanic rocks erupted since about 36 million years ago. Included in this thick accumulation are lahar deposits, tuffs of various types, and felsic to intermediate lava flows. These older volcanic rocks appear to be related to subduction of the Farallon plate. Younger basaltic (more mafic) lava flows in the region are about 3 million to 8 million years old and probably signify a shift from subduction-related volcanic activity to the rifting-related eruptions. The prominent normal faults are relatively young, displacing the entire succession of volcanic rocks.

Numerous hot springs and "mud volcanoes" occur along a north-to-south zone near the base of the Warner Range, within the Surprise Valley fault zone. Exploratory drilling along the fault zone has encountered water as hot as 170° F at depths from 500 to 1,500 meters (1,600 to 4,900 feet). This geothermal activity probably reflects the interaction between water moving down from the surface and hot young volcanic rock in the subsurface. Since 1984, the hot water from the Surprise Valley springs has been used to heat schools and hospitals in the small communities of the valley. In 1993 alone, this saved roughly $50,000 in fossil fuel costs.

The Lake Tahoe Graben: Though it rests along the eastern edge of the Sierra Nevada physiographic province, the geological structure of the Lake Tahoe basin is similar to the grabens of the Basin and Range province. This magnificent lake fills a deep depression created by normal faulting to a depth of nearly 500 meters (more than1,600 feet). Volcanic activity 3 million to 4 million years ago created a natural dam of basalt and andesite at the north end of the graben that blocked the drainage of the upper Truckee River. The basin-forming normal faults are still active in

▶ **Figure NC.48** Several scarps mark the trace of active faults on the floor of the Lake Tahoe Basin. Note the large blocks of rock on the lake bottom that document an ancient catastrophic landslide.

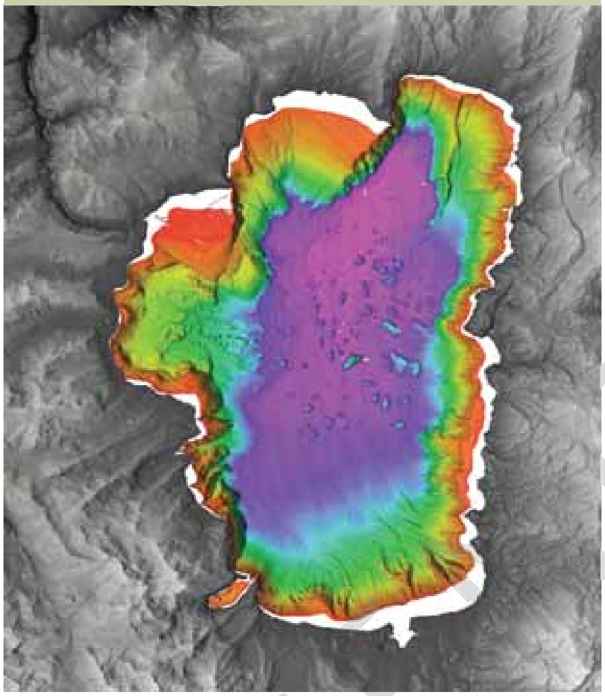


Image courtesy of the U.S. Geological Survey

the Lake Tahoe region, producing many small to moderate earthquakes. Ancient landslide rubble on the floor of Lake Tahoe is thought to have resulted from a major landslide triggered by a powerful Ice Age earthquake. Recent imaging of the lake (Figure NC.48) reveals numerous fault scarps resulting from recent displacement, a further indication of active faulting.

Section Northern California.7 Summary

- The Basin and Range province of extreme northeast California is a landscape of alternating mountains and valleys that extends eastward into Nevada and adjacent states. The corrugated terrain is the result of intense normal faulting caused by the tensional stresses that affect the entire Basin and Range region of western North America. The mountain blocks such as the Warner Range represent the footwall (or horsts) of the normal faults, whereas basins such as Surprise Valley represent the downthrown grabens. The Honey Lake and the Lake Tahoe basins also developed as grabens displaced downward by normal faults along the eastern edge of the Sierra Nevada province.

- The Warner Range is the most prominent mountain range of northeast California, and is composed primarily of Cenozoic-age volcanic rocks. Hot springs and mud volcanoes along the fault zone at the base of the eastern escarpment indicate the presence of young and hot volcanic rock in the shallow subsurface. These hot springs have been used locally as a source of energy for space heating.

- The Lake Tahoe basin lies in a graben that developed through the downward displacement of rocks along normal faults to the east and west. The elongated graben slopes gently to the north, and was blocked by lava flows that erupted 3 million to 4 million years ago. The natural volcanic dam impounded the waters of the ancestral Truckee River, creating the beautiful alpine lake. Ongoing seismic activity in the Lake Tahoe region suggests that the normal faults are still active and the basin is still evolving.

Northern California.8
The Northern California Ice Ages

During the Pleistocene Epoch, 1.8 million to about 10,000 years ago, all of the regions of northern California were affected by multiple climatic oscillations. In the higher elevations of the Sierra Nevada, Klamath Mountains, and the Cascade Range, numerous valley glaciers formed, and in the basins of the Great Valley and Basin and Range, lakes grew as water accumulated in the lower terrain (Figure NC.49). Even the coastal regions were affected, because sea level fell when the glaciers were expanding and rose when they were in retreat. Based on evidence from the Sierra Nevada, where the effects of the Pleistocene glaciers are most striking, geologists have identified four major glaciations corresponding to periods of cool climatic conditions. Some of these glaciations appear to be comprised of multiple cycles of glacial growth and decline. The glacial periods were separated by warm interglacial intervals when glaciers melted back and the lowland lakes diminished. The multiple ice ages of the Pleistocene Epoch in northern California signify a period of erratic oscillation in climate, not a long interval of enduring cold.

Because of their oscillatory nature, establishing a detailed and accurate history of glacial events from the geological evidence is difficult in most places. Each glacial advance tends to obliterate or obscure the evidence for the previous one. Geologists are in general agreement, however, that the two most recent glacial epochs in northern California peaked at about 160,000 years ago (the Tahoe glaciation) and 20,000 years ago (the Tioga glacation). Of these two glaciations, the earlier Tahoe appears to be longer and more severe than the later Tioga. There is also geologic evidence for earlier glaciations, but it is more fragmentary and localized than for either the Tahoe or the Tioga event.

► **Figure NC.49** Donner Lake in the northern Sierra Nevada, rests in a U-shaped glacial trough carved by Pleistocene glaciers.

Frank DeCourten

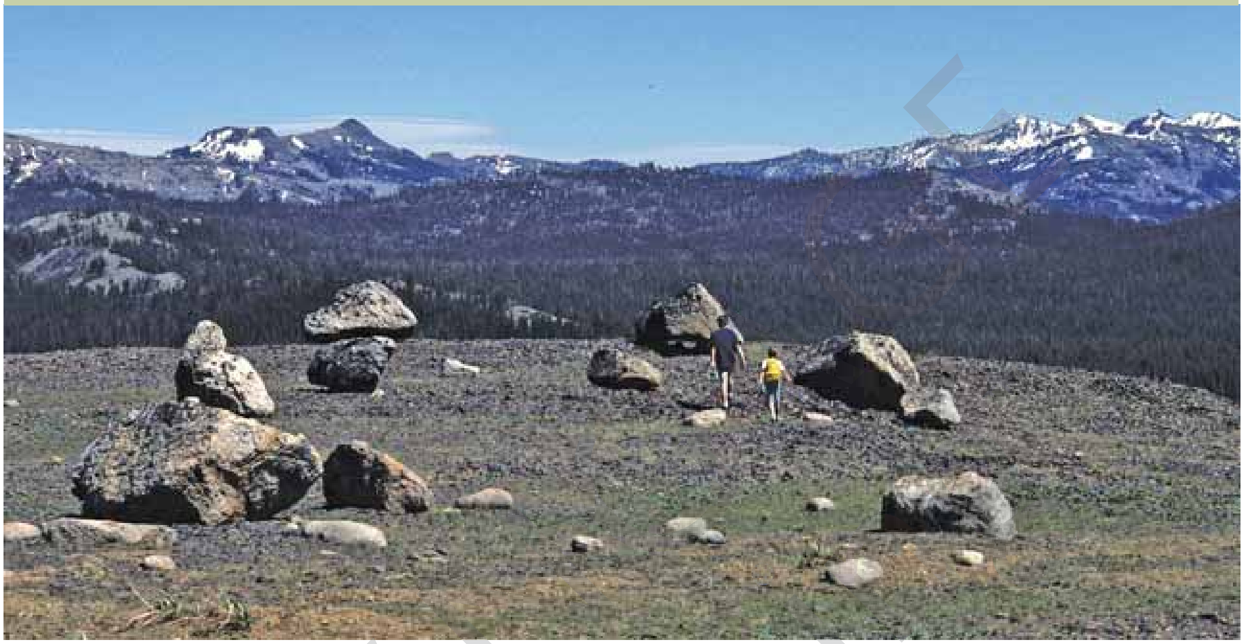
Effects of Valley Glaciers: The overall effect of glacial erosion in mountainous regions was to increase the relief and sharpness of the landscape through the development of U-shaped glacial troughs, **horns, arêtes**, and **cirques**. Although these landforms are displayed in spectacular fashion around Yosemite National Park in the central Sierra Nevada, they are also present in many other mountain regions of northern California. Wherever the Pleistocene glaciers existed, glacial **polish** and **striations** on bedrock surfaces are common (Figure NC.50). Such erosional features are widespread in the Trinity Alps, in the higher peaks of the Cascade Range, and in the alpine terrain west and south of Lake Tahoe. The Pleistocene-age valley glaciers also left extensive deposits of **moriane** of several types in these same mountain areas, along with **glacial erratics** (Figure NC.51).

► **Figure NC.50** Glacial striations on bedrock the northern Sierra Nevada.

Frank DeCourten

Lowland Lakes and Wetlands: During the cool climatic intervals of the Pleistocene Ice Ages, increased precipitation and reduced evaporation led to the development of large lakes and wetlands in the lower areas of northern California. Ice Age lakes that form in response to cool climate cycles are known as **pluvial** lakes and there were several of them at various times in the Honey Lake basin, in Surprise Valley, and in the Great Valley. In the Great Valley, large lakes formed repeatedly during the Pleistocene Epoch. One of the largest Ice Age lakes in the Great Valley existed between 800,000 and 600,000 years ago and covered the entire valley from its north end to the southern extremity. At other times, there were several smaller lakes with

Figure NC.51 Erratics of light-colored granite perched on dark-colored volcanic bedrock in the northern Sierra Nevada.

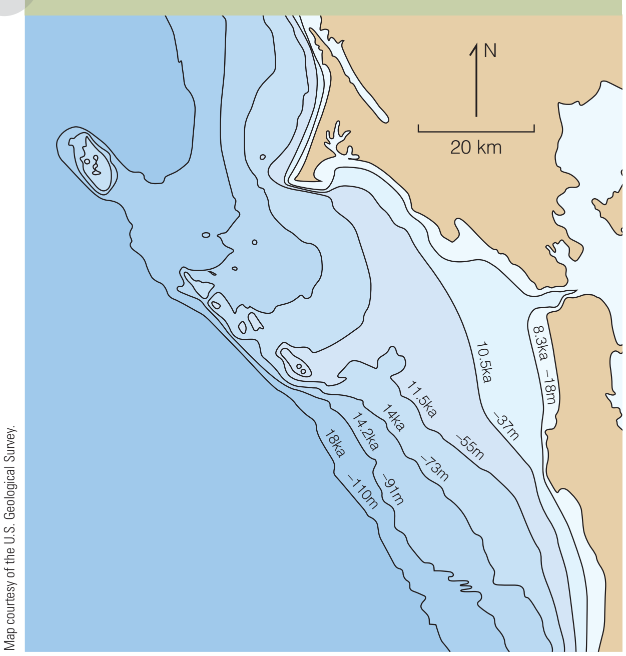


Dick Hilton

extensive wetland habitats between them. The lush native vegetation provided forage for a remarkable menagerie of Ice Age creatures, including giant bison, elk, ground sloths, mammoths, large cats, and bears. The remains of these creatures have been found in excavation sites throughout the Great Valley.

The Ice Age Landscape of San Francisco Bay: Earlier than about 600,000 years ago, the Sacramento and San Joaquin Rivers did not flow to the Pacific Ocean via San Francisco Bay as they now do. Instead the drainage from the surrounding highlands accumulated in one or more lakes in the Central Valley. Tectonic activity in the northern Coast Ranges had already produced a valley where the bay now is, but only local streams flowed into and through it. Sometime after 600,000 years ago, water from central California began to flow into the San Francisco Bay, where it mingled with ocean water to create the large estuary that exists today. However, cycles of climate change during the Late Pleistocene caused sea level to fluctuate several times. During cool intervals leading to glacial advances, sea level fell by as much as 120 meters (390 feet), causing water to withdraw from San Francisco Bay to the west. About 20,000 years ago, for example, the shoreline of the Pacific Ocean was located beyond the Farallon Islands, more than 30 kilometers (18 miles) west of the modern Golden Gate Bridge. At that time, San Francisco Bay was a broad river valley where streams from the Great Valley met with local tributaries before turning west through a valley that then existed in the Golden Gate area. Since about 20,000 years ago, the climate has become warmer, the Late Pleistocene glaciers melted, and sea level rose. By about 8,000 years ago, sea water had once again invaded San Francisco Bay to re-establish the estuary of modern times (Figure NC.52).

Figure NC.52 Sea level rise over the past 20,000 years has converted the San Francisco Bay area from a river valley to an estuary.



Map courtesy of the U.S. Geological Survey.

Section Northern California.8 Summary

- During the Pleistocene Epoch, California was affected by multiple cycles of climatic oscillations. Cool intervals resulted in the growth of valley glaciers in the higher elevations of the Sierra Nevada, Klamath Mountains, and the Cascade Range, and pluvial lakes developed in the lowlands.

- The two best documented glacial intervals are the Tioga glaciation about 20,000 years ago and the preceding Tahoe glaciation that peaked about 160,000 years ago. Both of these glacial intervals involved multiple advances and retreats that reflect the climatic oscillations of the Pleistocene. There is evidence of earlier glaciations, but the precise chronology and extent for them has yet to be determined with certainty.

- Valley glaciers in the mountainous regions carved U-shaped valleys and sculpted arêtes, horns, and cirques in bedrock exposures. Moraines and glacial erratics can also be identified in most mountains above 2,000 meters in elevation.

- In the lower elevations of the Basin and Range and Great Valley, pluvial lakes expanded and declined in rhythm with the Pleistocene climatic cycles. The largest of these Ice Age lakes submerged the floor of the entire Great Valley between 600,000 and 800,000 years ago.

- Sea level rose and fell multiple times during the Pleistocene Ice Ages. During times of glacial advances, sea level fell as much as 120 meters. Under such conditions, San Francisco Bay was a river valley through which rivers carried water to the Pacific coast located about 30 kilometers west of the modern shore. When the California glaciers melted during warm interglacial intervals, sea level rose. The modern estuary in San Francisco Bay formed about 8,000 years ago as glaciers in the interior mountains were melting under the influence of a warming climate.

Northern California.9
Northern California Earthquakes

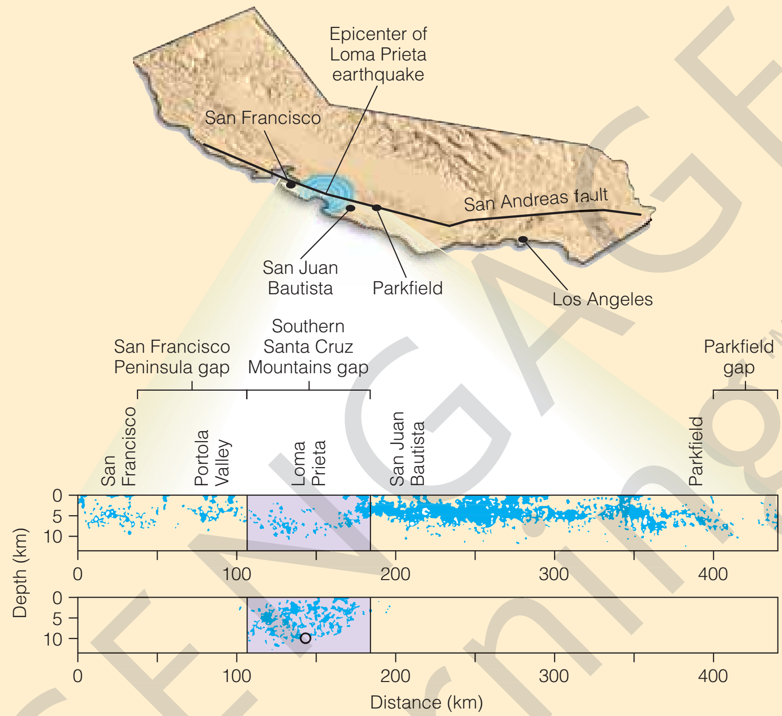
Earthquakes in California are an inevitable consequence of the interactions between tectonic plates along the forward edge of a west-moving continent. The forces generated along the transform boundary between the Pacific and North American plates, and at the convergent boundary between the Juan de Fuca and North American plates, result in thousands of earthquakes every year. The ground literally shakes continuously in California, but most of these tremors go unfelt by people and rarely cause damage. Nonetheless, the seismic history of northern California includes some devastating events that provide a chronic reminder of the natural hazards facing those who live near a plate boundary. The infamous 1906 San Francisco earthquake (estimated magnitude 7.8 on the Richter scale) occurred along a segment of the San Andreas fault more than 400 kilometers long, ignited fierce building fires, and claimed more than 2,000 lives. In 1989, the magnitude 6.9 Loma Prieta earthquake in the Santa Cruz Mountains left 62 people dead in the San Francisco Bay area and caused nearly $10 billion in damages. In the dynamic tectonic environment of northern California, where millions of residents live in close proximity to active faults, future seismic disasters are as certain as those of the past have been tragic.

Earthquakes in northern California are associated with three different plate tectonic settings. The San Andreas fault system, including scores of subsidiary faults, generates many tremors in the San Francisco Bay area and the northern Coast Ranges. These earthquakes release stress associated with the northward motion of the Pacific plate along the edge of the North American plate. The earthquakes generated along this plate boundary tend to have very shallow foci, less than 15 kilometers deep (Figure NC. 53), and can be very powerful. In the densely populated urbanized area around San Francisco Bay, many buildings have been constructed on soils or bedrock that are not very resistant to seismic vibrations. In both the 1906 San Francisco and the 1989 Loma Prieta earthquakes, intense ground shaking, liquefaction, and fire all contributed to scope of the disaster and were related to the poor response of weak soil or rock to earthquake vibrations.

The second area of notable seismic activity is associated with the Mendocino triple junction along the northern coast, where each year 80 to 100 earthquakes greater than magnitude 3 occur. Here, forces generated as the Juan de Fuca (Gorda) plate descends into the Cascadia subduction zone can produce powerful earthquakes in a zone that dips eastward beneath the continent. In this plate tectonic setting, earthquakes occur in both the oceanic plate and on land, including some that can be powerful. In July and August of 1991, four major earthquakes, ranging from magnitude 6.3 to 7.1, occurred near the Mendocino triple junction, and there is good geologic evidence for even larger prehistoric events, possibly as great as magnitude 9. In addition to the impacts of local communities, large coastal earthquakes in northern California have the potential to produce **tsunamis** that could affect distant regions bordering the Pacific Ocean.

Along the eastern side of the Sierra Nevada, active normal faulting associated with the continuing uplift of the mountain block produces a third zone of seismic activity from the Lake Tahoe area south to Owens Valley. The eastern Sierra earthquakes are mostly generated along normal faults, but several prominent strike-slip faults in the region indicate that both tension and shear stresses exist in this area. Although the majority of eastern Sierra earthquakes are small, several greater than magnitude 6 have occurred

▶ **Figure NC.53** Distribution of earthquake foci along the San Andreas Fault from San Francisco to Parkfield. Note that most earthquakes occur within 15 km of the surface. The seismic gap filled by the 1989 Loma Prieta earthquake is represented on the bottom panel.



in the past 40 years. In Lone Pine, along the southern portion of the Sierra Nevada fault system, an 1872 earthquake destroyed all but seven houses and killed no fewer than 27 people. This earthquake occurred before seismometers were developed, but it may have been California's most powerful historic temblor. A recurrence of such an earthquake along the Sierra Nevada fault system would have major impacts on the resort communities in the Reno-Tahoe area, and regions farther south.

Earthquake Forecasts in Northern California: Even though scientists have been intensely studying earthquakes in California for more than a century, no reliable means to predict their occurrence with precision has been developed. Instead, geologists can forecast the probabilities of future earthquake occurrences based on measurements of ground motion and strain, historic patterns of seismic activity, and geologic evidence of fault activity. In recent years, the analysis of **seismic gaps**, seismically "quiet" segments along active faults, has helped to identify places most prone to future earthquakes. Because no two faults are exactly the same, the forecasts for major earthquake potential vary across the state, from very unlikely in some places to almost certain in others.

The time frame is a key consideration in making and using earthquakes forecasts. Over the long span of geologic time, the probability of a major earthquake in California is 100%, but the likelihood of such an event tomorrow is very low. Geologists generally try to forecast earthquakes over periods of 20 to 50 years to coincide with the time frames most widely used by planning commissions, disaster response agencies, and the insurance industry. In 1989, the U.S. Geological Survey developed the first widely accepted earthquake forecast for the San Andreas fault system. This forecast estimated the probabilities for major earthquakes between 1988 and 2018 within the entire fault zone. The probabilities varied from 10% to 90% at various locations along the fault system. Interestingly, the Loma Prieta earthquake occurred in an area where a seismic gap had been identified in this study (see Figure NC.53).

In 2007, an interdisciplinary team of scientists known as the Working Group on California Earthquake Probabilities developed a new updated earthquake forecast called the Uniform California Earthquake Rupture Forecast, Version 2 (UCERF). The new forecasts involve a broader array of data and techniques for estimating probabilities than did earlier assessments. Statewide, the UCREF estimates the probability of a magnitude 6.7 earthquake in the next 30 years at more than 99%. Californians also face a 46% chance of experiencing a magnitude 7.5 or larger earthquake in the same time frame.

▶ **Figure NC.54** Major faults of the San Andreas system in the San Francisco Bay Area. This map from the United States Geological Survey also identifies features resulting from recent offset along these faults by the circled numbers.

Map courtesy of the U.S.Geological Survey.

In northern California, the probabilities are lower than for the state as a whole. UCERF estimates that there is a 93% chance of a magnitude 6.7 or greater earthquake in the northern part of the state, with a 63% chance of the temblor occurring in the San Francisco area (Figure NC.54). The faults most likely to produce this large earthquake are the Hayward-Rogers Creek (32% probability), San Andreas (21% chance), and Calaveras faults (18% probability). The UCERF estimates only a 2% probability for an earthquake of magnitude 8 in northern California, illustrating that very large earthquakes are rare, even along the San Andreas fault system. This may seem comforting, but we should not forget how disastrous earthquakes in the magnitude 6 to 7 range have been in California. Earthquakes in this range of magnitude have resulted in more than $65 billion in property losses in California since 1971.

Living with Earthquakes in Northern California: Although human activities such as underground fluid injection can initiate earthquakes, such practices to reduce the earthquake threat in northern California would be extremely risky. There is no way to guarantee the size, location, or duration of such an induced earthquake, and even a moderate temblor could have disastrous consequences in densely populated areas. In the absence of any safe mechanism to control seismic events in California, careful planning and preparation for them makes good sense.

The California Geological Survey, the United States Geological Survey, and the California Office of Emergency Management have collaboratively developed forecast models and seismic hazard maps that are used to plan communities and make preparations for coordinated responses to earthquakes. In addition, in the most sensitive areas, stringent building codes have been developed that result in more earthquake-resistant structures. Local zoning ordinances in many areas limit residential and commercial development in locations where strong ground shaking or liquefaction are anticipated. Personal preparation is also important, and checklists are available at the aforementioned agencies that provide guidelines for preparing homes and apartments for a potential earthquake. The combination of continuing earthquake research, careful planning, stringent building codes, wise land use, and personal preparation is the best way to limit the property damage and loss of life in future northern California earthquakes.

Section Northern California.9 Summary

- Northern California earthquakes occur as a consequence of convergent plate interactions in the Cascadia subduction zone, in relation to the transform boundary between the Pacific and North American plates to the south, and along the normal fault zone at the base of the eastern escarpment of the Sierra Nevada. The San Andreas fault zone, part of the transform plate boundary, has historically produced the most large earthquakes, but destructive earthquakes could occur in the other plate tectonic settings in northern California as well.

- Earthquakes in populated regions of northern California have resulted in intense ground shaking leading to collapse of structures, liquefaction, landslides, and fires that have claimed many lives and caused billions of dollars of property damage. The 1906 San Francisco and the 1989 Loma Prieta earthquakes were the two most destructive earthquakes in northern California history.

- Geologists can formulate earthquake forecasts along active faults on the basis of ground motion and strain measurements, historic seismicity including "quiet" segments known as seismic gaps, and geological evidence of prehistoric fault activity. The most recent forecasts estimate the probability of a magnitude 6.7 or greater earthquake in northern California at 67%. Faults in the San Francisco Bay area within the San Andreas fault zone are most likely to produce this future earthquake.

- Because it is currently impossible for humans to prevent or weaken earthquakes, preparation for them is essential in reducing their impacts on people. In northern California, continued monitoring of active faults coupled with wise land use regulations, stringent building codes, and effective response plans will substantially reduce the impacts of future earthquakes.

Northern California.10
Living on the Edge: Coastal Hazards in Northern California

With 1,800 kilometers (1,120 miles) of ocean frontage, California has more coastline than all but two other states, Florida and Alaska. The northern portion of the California coast trends northwest, directly facing the enormous and tectonically active Pacific Ocean basin. Winter storms approach the exposed northern coast from the open ocean, bringing with them powerful wind-generated waves. In addition, normal wind swells, longshore currents, and occasional tsunamis also strike the north coast with full force. In contrast, the east-to-west alignment of much of the southern California coast partially protects the shoreline from the vigorous erosion experienced in the north. Consequently, the northern California coast is rugged and rocky rather than broad and sandy (Figure NC.55). Some locations along the north coast, such as Big Sur and Mendocino, are world famous for their spectacular coastal scenery.

The California coast also is unique in its recent emergence and in the variety of rock types exposed along the steep seashore. Recall from our earlier discussions that mountains of the northern Coast Ranges have been elevated over just the past several million years and, in fact, are still rising. The coast of northern California is therefore an **emergent** coast, where the land is being lifted by tectonic forces relative to sea level. As bedrock rises from the seafloor, it is exposed to the various agents of coastal erosion. In most places, the uplift exposes rocks of the heterogeneous Franciscan complex or the Salinian terrane. These rock assemblages include both easily eroded materials such as marine shale or sandstone and more durable igneous and metamorphic rocks such as granite, basalt, and greenstone. The erosion of such mixed

Figure NC.55 The steep and rugged shore in Point Reyes Nationa Seashore is typical of the scenic coast of northern California. Note the nearly flat marine terrace above the sea cliffs.

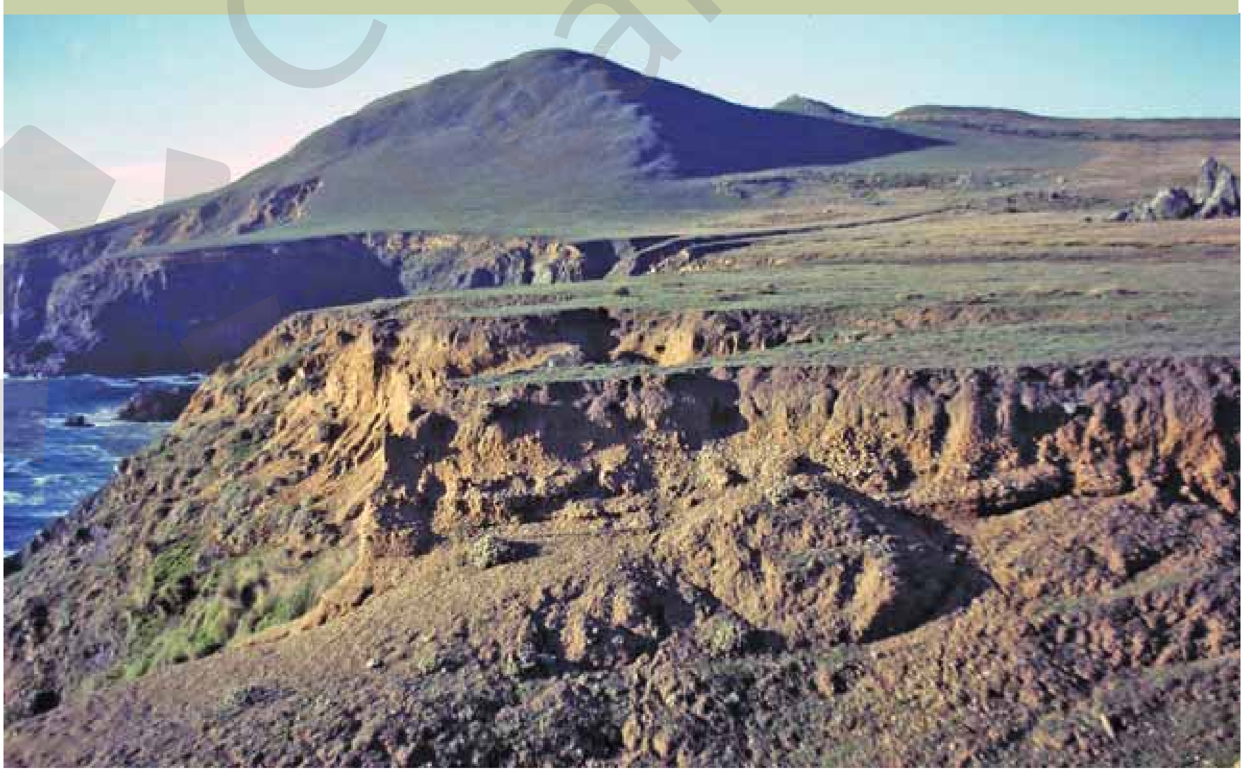


Photo courtesy of the U.S. Geological Survey.

▶ **Figure NC.56** A pocket beach developed between projecting headlands on the Monterey Peninsula.

Photo courtesy of the U.S. Geological Survey, Center for Coastal Geology.

bedrock assemblages produces an irregular coastline, with coves and **pocket beaches** developing where soft rocks exist and **headlands** (Figure NC.56) projecting where harder rocks are exposed.

Coastal Landforms of Northern California: Because of the pervasive coastal emergence, the shoreline landforms in northern California are mostly of erosional origin. Sea cliffs and wave-cut platforms are actively forming in many locations, and elevated marine terraces are commonly observed above the coastal bluffs (Figure NC.57). Because the marine terraces originated as wave-cut platforms near sea level, geologists can estimate the rate of uplift along the coast by establishing the age of the terraces using fossils preserved on their surfaces. Radiometric ages for fossil material from the terraces suggest that the most prominent surfaces rose to their present elevation at rates varying from about 28 to 45 centimeters per thousand years in the Santa Cruz and Monterey Bay areas. Farther north, in the Mendocino area, the rate of emergence is even higher. This helps explain why the coast of California shows such strong emergent features, even though sea level has been

▶ **Figure NC.57** A marine terrace along the northern California coast with remnant sea stacks. Note the younger sea stacks forming along the modern coast.

James S. Monroe

▶ **Figure NC.58** Sea stacks along the northern Califonria coast at Shell Beach.

Sue Monroe

rising for the past 20,000 years. The land simply is rising faster than the sea.

Sea cliffs along the north coast are continuously undercut by waves generated during powerful winter storms. Because waves approaching a projecting headland are refracted around it, the wave-cut notches in some areas can develop into **sea caves** on opposite sides of the bedrock exposure. Continued wave erosion can deepen the caves until they connect, forming a **sea arch** (see Figure NC.26). **Sea stacks** (Figure NC.58), isolated exposures of bedrock, represent remnants of sea arches that have collapsed as a consequence of a continued wave erosion. The long-term effect of the formation of wave-cut platforms, sea caves, sea arches, and sea stacks along an emergent coast is the steady landward retreat of the cliffs. This has placed many coastal developments at risk along the northern California shoreline.

In addition to erosional features, depositional landforms have also developed in some areas along California's north coast. In places where streams discharge into bays or coves, **spits** (Figure NC.59) and **baymouth bars** (Figure NC.60) can develop from the accumulation of sediment transported by both rivers and longshore currents. **Tombolos**, sand spits that extend from the shore to a sea stack, can also be seen in several places along the northern California coast (Figure NC. 61). Tombolos are generally rare, but the abundance of sea stacks along the emergent northern California coast has created many places where the conditions exist under which tombolos form.

***Coastal Hazards in Northern California*:** The majority of California's population lives within 100 kilometers (60 miles) of the coast. In northern California, the rugged beauty of the seashore has resulted in extensive residential and recreational development along the rapidly eroding emergent coast. Geologists have determined that coastal erosion is causing some sea cliffs in northern California to retreat at rates as high as 1.1 meters (3 feet) per year. In spite of recent regulatory action to restrict coastal development, there are

▶ **Figure NC.59** A spit at the mouth of the Russian River.

James S. Monroe

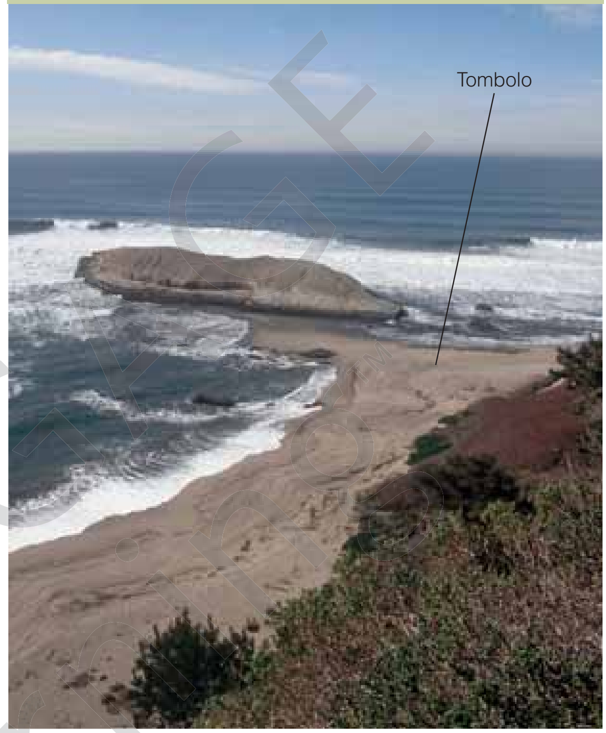
▶ **Figure NC.60** A baymouth bar in Marin County, California.

James S. Monroe

still hundreds of miles of coastline in northern California where people and property are threatened by retreating cliffs and unstable ground.

The principal hazard along the northern California coast is **mass wasting** triggered by wave undercutting, heavy rainfall, or earthquakes. Rock slides and slumps have repeatedly caused extensive damage to structures perched above sea cliffs (Figure NC.62). These problems are most severe where the bedrock is soft, sheared, or water saturated. Unfortunately these conditions are common along the tectonically active north coast, which is underlain by the highly deformed rocks such as those comprising the Franciscan complex. Mass wasting activity along the northern coast also extends offshore and down the continental slope. Turbidity currents initiated by earthquakes or storm events have scoured several impressive submarine. Monterey Canyon, the largest submarine canyon on the Pacific Coast, is deeper than the Grand Canyon and extends offshore for more than 400 kilometers (250 miles).

▶ **Figure NC.61** A small tombolo connecting the shore to a sea stack remnant in northern California



Sue Monroe

▶ **Figure NC.62** Mass wasting in Bodega Bay resulted from undercutting of the sea cliff by waves generated during winter storms of 1997–1998.

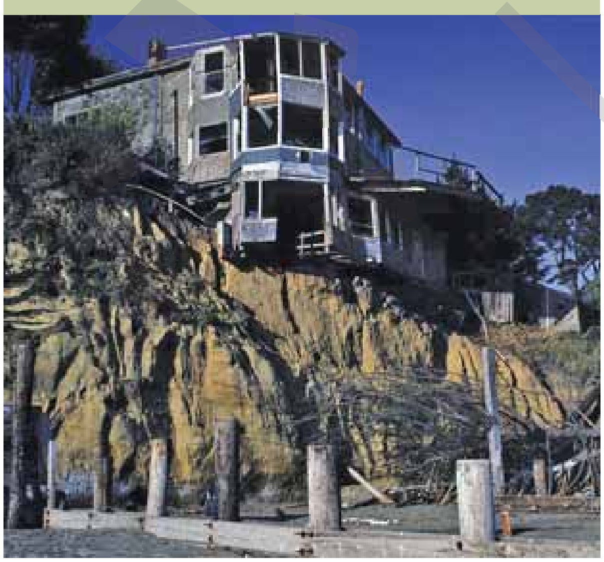
James S. Monroe

Because the northern California coast faces the Pacific Ocean basin where strong earthquakes occur frequently, tsunamis pose an additional hazard. Tsunamis can travel thousands of miles from their source, so even earthquakes in Japan or South America could affect people in northern California. In fact, the principal tsunami threat to northern California may be distant, not local, earthquakes. This is because the dominant strike-slip motion along the San Andreas fault system, much of which is on land, would not likely produce large vertical displacements on the seafloor. Subduction-related earthquakes generated in convergent plate boundaries more commonly result in the type of displacement that initiates tsunamis.

In April 1964, a 7-meter (23-foot) tsunami generated by the magnitude 9.2 Alaskan Earthquake struck Crescent City on the north coast, resulting in 11 deaths and an estimated $15 million in property damage. In the same town, a boat harbor suffered $10 million in damages from a tsunami that struck in November 2006. Other coastal towns in northern California to experience tsunami damages include Eureka, Half Moon Bay, and Santa Cruz. A major earthquake in the nearby Cascadia subduction zone is a primary concern in these coastal areas because it could potentially produce a much more disastrous tsunami than any experienced thus far. There is good geologic evidence of a major earthquake, perhaps as large as magnitude 9, in this area 300 years ago that may have caused a tsunami in Miho, Japan. Fortunately, most populated areas along the northern California coast have tsunami warning systems and evacuation plans in place.

Human Activities and Coastal Hazards: Although mass wasting and wave erosion are natural processes along California's north coast, they have been intensified and triggered in places by human activity. Whenever an ocean-facing slope or shore is modified for construction of roads or buildings, there is potential for otherwise stable slopes to fail. Highway 1, along the north coast, has experienced repeated closures due to mass wasting events. Property damage associated with mass wasting along this scenic highway has been significant in such coastal communities as Bolinas, Stinson Beach, and Pacifica (Figure NC.63). Farther south along the same highway at Half Moon Bay, a breakwater completed in 1961 to protect the harbor resulted in a fourfold increase in the rate of coastal erosion to the south. This was the natural response to the interruption of the southward flow of sand along the beach and the refocusing of wave energy produced by the breakwater. Many cities and planning commissions carefully review proposals for coastal development in an effort to reduce the negative impacts that result from altering natural slopes and shores. However, much of the development along the north coast was approved before the impacts of human activity were fully evaluated or understood. Coastal erosion will continue to be a concern for residents of California's scenic north coast.

▶ **Figure NC.63** Coastal erosion in northern California threatens thousands of homes such as this one near Bolinas.



Dick Hilton

Section Northern California.10 Summary

- The northern part of California's long coastline directly faces the Pacific Ocean and is vigorously eroded by wind waves, storm events, longshore currents, and occasional tsunamis. In addition, geologic forces are still lifting the Coast Ranges faster than sea level is rising so that new bedrock continuously appears along the emergent coast. In many coastal locations, the emerging bedrock is a mixed assemblage of hard and soft rock such as the Franciscan complex that does not respond uniformly to the agents of erosion. The combination of these factors produces an irregular and spectacularly rugged coast with many projecting headlands and small coves and pocket beaches.
- Erosional landforms such as wave-cut platforms, sea cliffs, sea caves, sea arches, sea stacks, and marine terraces dominate the scenery along the emergent coast of northern California. In places where rivers deposit sediments along the coast, or where longshore currents are active, sand can accumulate to form depositional features such as spits, baymouth bars, and tombolos.
- Many people live near the actively eroding coast in northern California. Coastal development is commonly at risk because of cliff retreat and mass wasting events that undermine support for structures. In addition, earthquakes in the Pacific Ocean basin can generate tsunamis that have affected several coastal communities. Human modifications, such as breakwaters, to protect portions of the coast can intensify erosion elsewhere and interrupt the transportation of sediment along the coast.

Review Workbook

ESSENTIAL QUESTIONS SUMMARY

Northern California.1 Introduction

■ *What are northern California's physiographic provinces?*
Physiographic provinces are regions of distinctive geology, landforms, climate, geomorphic trends, soils and vegetation, and drainage. In northern California, seven physiographic provinces are recognized: the Sierra Nevada, the Klamath Mountains, the Great Valley, the Coast Ranges, the Cascade Range and Modoc Plateau, and the Basin and Range. Collectively, these provinces endow northern California with extraordinary geologic diversity.

■ *What is the Farallon subduction zone?*
The Farallon subduction zone developed at the convergent plate boundary between the North American and Farallon plates about 200 million years ago. The entire subduction zone persisted until about 30 million years ago, when portions of it were disrupted by the collision between North America and the Farallon-Pacific spreading ridge. Many of the major geologic features of northern California resulted from the convergence of plates in the Farallon subduction zone.

■ *What two types of plate boundaries exist in northern California today?*
North of Cape Mendocino, the Juan de Fuca plate, a remnant of the Farallon plate, continues to be subducted under continental lithosphere to the east. South of Cape Mendocino, the transform boundary between the Pacific and North American plates shapes the geologic setting of northern California. The San Andreas fault system is directly related to the transform boundary, whereas northern California's volcanic centers are related to the subduction process.

■ *What are terranes, how do they originate, and why are they important in northern California?*
Terranes are large blocks of rock, typically bounded by faults, representing seamounts, oceanic rises, reefs, island arcs, or other oceanic features accreted to continents at convergent plate boundaries. Terranes are comprised of exotic rocks that become detached from a subducting plate and are sutured to the edge of the overriding continent. In northern California, many terranes accreted over the past 500 million years have been identified by geologists.

Northern California.2 The Sierra Nevada: California's Geologic Backbone

■ *What is the Sierra Nevada batholith?*
The Sierra Nevada batholith is a large body of plutonic rock that comprises the core of the Sierra Nevada, California's best known mountain system. It consists of more than 100 individual plutons emplaced mostly between 140 million and 80 million years ago.

■ *What kinds of rocks surround the Sierra Nevada batholith?*
Metamorphic rocks of Paleozoic and Mesozoic age surround the Sierra Nevada batholith. Most of these rocks are of oceanic origin and represent terranes accreted to North America before the intrusion of magma into the batholith during the Mesozoic Era.

■ *When and how was the modern Sierra Nevada uplifted?*
Though the Sierra Nevada region may have been elevated since the late Mesozoic Era, a pulse of rapid uplift 5 million to 10 million years ago lifted the mountain range to its present height. The recent ascent occurred via normal faulting and westward tilting along the eastern escarpment of the range.

■ *What types of gold deposits occur in the Sierra Nevada?*
Gold occurs in the Sierra Nevada regions as particles in modern river sediments (placer deposits), as flakes and nuggets in Eocene-age stream deposits known as "auriferous" gravels, and in association with quartz veins, or lodes, in Mesozoic-age basement rocks.

■ *What is the Mother Lode?*
The Mother Lode is a northwest-trending belt of gold mineralization in the Sierra Nevada foothills. Along this trend modern placer deposits, ancient gold-bearing river sediments, and lode deposits associated with quartz veins have all produced significant amounts of gold.

Northern California.3 The Klamath Mountains

■ *In what ways are the Klamath Mountains and the Sierra Nevada Similar?*
In both the Sierra Nevada and the Klamath Mountains bodies of Mesozoic-age granite have been emplaced in older metamorphic rocks representing numerous terranes accreted to North America. Gold mineralization is common to both areas as well, but slices of oceanic lithosphere (ophiolites) are more common in the Klamath Mountains than in the Sierra. In general, the Klamath Mountains represent a northwest continuation of the geological trends of the Sierra Nevada.

■ *What kinds of rocks comprise the ophiolites in the Klamath Mountains?*
Ophiolites represent disrupted fragments of oceanic lithosphere consisting of mafic and ultramafic igneous rocks associated with oceanic sediments. During emplacement of ophiolite sequences on land by plate convergence, the oceanic rocks generally became deformed and metamorphosed to greenstone, serpentinite, schists, and other altered materials.

Northern California.4 The Great Valley

■ *What factors have led to the formation of fertile soils in the Great Valley?*
The soils of the Great Valley have developed on alluvium derived from the weathering granitic and volcanic bedrock in the Sierra Nevada and adjacent ranges and deposited on a nearly flat surface by the Sacramento and San Joaquin River systems. These factors, along with the warm climate and abundant organic matter of the Central Valley, promote the formation of nutrient-rich, water-retaining soils that can support high agricultural productivity.

■ *What was the origin of the sedimentary rocks in the Great Valley Sequence?*
The Great Valley Sequence consists of sandstone, mudstone, and shale that accumulated in a forearc basin associated with the Mesozoic Farallon subduction zone. These rocks include sediments that were transported by turbidity currents to the deep seafloor where they built large submarine fans.

■ *What is the origin of the natural gas produced in the Great Valley?*
The natural gas resources of the northern Great Valley (Sacramento Valley) originate from organic matter trapped underground in the oceanic sediments of Mesozoic and Cenozoic age.

■ *Why is the Great Valley so prone to chronic flooding?*
The Great Valley is remarkably flat, surrounded by elevated terrain that receives abundant rain and snow, and has a climate that can produce both heavy winter rains and rapid spring melt of snow. The broad floodplain adjacent to the Sacramento and other rivers in the Great Valley has developed over thousands of years of recurring floods. The natural flooding behavior of rivers in the Great Valley is a serious threat to the populous cities, large farms, and industrial centers that have been established in the region.

Northern California.5 **The Northern Coast Ranges**

■ *What is the Franciscan complex and how did it form?*

The Franciscan complex is a complex assemblage of deformed rock consisting of oceanic sediments such as graywacke, shale, and chert mixed with metamorphosed igneous rocks. Such a complex rock mixture is known as a mélange, and represents an amalgamation of rock that formed in the Farallon subduction zone.

■ *How did the San Andreas fault system originate?*

The San Andreas fault system is the consequence of the development of a transform boundary between the North American and Pacific plates over the past 30 million years. The faults in the San Andreas system are mostly right-lateral strike-slip faults that accommodate the displacement between the Pacific plate (moving to the northwest) and the North American plate.

■ *What is the Salinian block?*

The Salinian block is a large terrane in the northern Coast Ranges that includes granitic and metamorphic basement rocks, similar to those of the Sierra Nevada, overlain by Cenozoic-age sediments of oceanic and terrestrial origin. From its original position near the south end of the Sierra Nevada, the Salinian block has been transported more than 300 kilometers northwest along the San Andreas fault system.

■ *How old are the northern Coast Ranges and what tectonic forces elevated them?*

The northern Coast Ranges are relatively young mountains, rising to their present elevations in the past 3 million to 4 million years. The forces that lifted these coastal mountains are probably related to compression between fault slices in the San Andreas system and the northward migration of the Mendocino triple junction.

Northern California.6 **Volcanoes of the Cascade Range and Modoc Plateau**

■ *What California volcanoes are part of the Cascade Range?*

Mount Shasta (elevation 4,319 meters/14.161 feet), Mount Lassen (elevation 3,188 meters/10,457 feet), and the Medicine Lake highland are the principal volcanic features of the Cascade Range in northern California.

■ *What is the Cascadia subduction zone?*

The Cascadia subduction zone generates the magma that sustains the volcanic activity in the Cascade Range. This subduction zone is created by the downward movement of the Juan de Fuca plate beneath the northwest edge of North America. The Cascadia subduction zone is only partly in northern California, extending northward from near Cape Mendocino to British Columbia.

■ *What kind of volcanic activity typifies the Cascade Range?*

Cascade volcanoes are mostly composite cone (or stratovolcanoes) that alternate between effusive eruptions of viscous andesitic lava and more violent explosive events that result in pyroclastic flows. The explosive phase of activity was most recently demonstrated by the 1980 eruption of Mount St. Helens in Washington, but the geologic record provides evidence of much more violent prehistoric activity in several Cascade Range locations.

■ *Why is Mount Lassen an especially interesting volcano in the Cascade Range?*

Mount Lassen is noteworthy among Cascade Range volcanoes because it is the most recently active volcano in California (it last erupted in 1914–1921) and is classified as a lava dome, not a composite volcano. Geothermal activity and ongoing seismic activity in the Mount Lassen region suggest that the underground magma system is still active.

Northern California.7 **The Basin and Range of Northeast California**

■ *What tectonic forces are responsible for the pattern of alternating mountains and valleys in the Basin and Range province?*

Tensional, or stretching, forces have broken the crust in the Basin and Range into hundreds of blocks bounded by normal faults. The blocks displaced downward (the hanging wall) along these faults are represented by the low valleys that separate the elevated ranges.

■ *What mountains and basins in northern California belong to the Basin and Range province?*

The Warner Range, more than 3,000 meters (9,870 feet) high, is the best example of a Basin and Range mountain system in northeast California. The adjacent Surprise Valley and the Lake Tahoe basin to the south both developed as a consequence of the downward displacement along normal faults.

Northern California.8 **The Northern California Ice Ages**

■ *During what time periods did northern California experience Ice Age conditions?*

Multiple cycles of climate change affected northern California during the Pleistocene Epoch, but the Tahoe and Tioga glaciations, about 160,000 and 20,000 years ago respectively, are the two best documented episodes.

■ *What landscape features resulted from the Pleistocene Epoch glaciations in northern California?*

Valley glaciers developed in the mountainous regions of northern California several times during the Pleistocene Ice Ages. Erosional features produced by these glaciers are widespread and include polished and striated bedrock surfaces, U-shaped glacial troughs, horns, arêtes, and cirques. In addition, sediments released from melting ice at the close of the glacial episodes left glacial erratics and moraine deposits in many locations.

■ *How did the Pleistocene landscape of northern California differ from the modern setting?*

During the periods of maximum glacial advance, the crest of the Sierra Nevada was buried under a thick ice cap. From this high mass of ice, valley glaciers extended down the major canyons, in some cases completely filling them with ice. Valley glaciers also existed in the Klamath Mountains and in the Cascade Range. In the lowland valleys, pluvial lakes expanded and withered repeatedly in rhythm with the Pleistocene climatic oscillations. The decrease in sea level that accompanied the glacial intervals exposed the floor of San Francisco Bay as a broad river valley several times. The Pacific shore was more than 30 kilometers west of its present location.

Northern California.9 **Northern California Earthquakes**

■ *What plate tectonic settings are associated with northern California earthquakes?*

Northern California earthquakes occur mostly along the San Andreas fault system (part of a transform plate boundary), in the Cascadia subduction zone (a convergent boundary), or along the eastern escarpment of the Sierra Nevada (a zone of developing plate divergence, or rifting).

■ *What is the likelihood of another major earthquake in northern California?*

Given the tectonic forces currently affecting the crust in northern California, another major earthquake is certain to occur eventually. Modern techniques for forecasting earthquake activity, including the analysis of seismic gaps, suggest that there is a 67% probability of an earthquake exceeding magnitude 6.7 in the next 30 years. The faults in the San Francisco Bay area, such as the Hayward-Rogers Creek, Calaveras, and San Andreas faults, are mostly likely to produce this earthquake. In this densely populated and intensively developed region, such an earthquake could have disastrous consequences.

■ *What might be the effects of a large northern California earthquake?*

Depending on the location of the epicenter and the magnitude, the ground shaking of a large earthquake in northern California could result in damaged or destroyed buildings, fires, collapsed bridges, disrupted communications and transportation networks, contaminated drinking water, liquefaction of soils, and tsunamis along the coast. Millions of people and billions of dollars in property are vulnerable to earthquake hazards in northern California.

■ *Given the severity of the potential hazards, how can the effects of earthquakes be minimized in northern California?*
Experience has shown that earthquakes hazards can be reduced through a combination of wise land use, continuous seismic monitoring, stringent building codes, and personal and public preparedness. Fortunately, most populated regions in northern California have plans in place for effective responses to a potential earthquake, and the regulated development of communities has reduced the number of people at risk.

Northern California. 10 Living on the Edge: Coastal Hazards in Northern California

■ *In comparison to the coast of southern California, why is the northern California shoreline so rugged and scenic?*
The northern California coast trends northwest, directly facing the waves, storms, and tsunamis generated in the Pacific Ocean basin. In addition, the emergent coast of northern California continuously exposes new bedrock to the vigorous erosion that results in such landforms as sea cliffs, sea caves, sea arches, and sea stacks. Finally, in most places, the bedrock of the northern California coast is a complex assemblage of hard and soft rock that erodes to an irregular shore with projecting headlands separated by recessed coves and pocket beaches.

■ *What coastal hazards exist in northern California?*
Coastal hazards in northern California are primarily related to erosion, mass wasting, or seismic activity. Erosion of sea cliffs by waves causes the cliffs to retreat at rates as high as a meter per year, potentially affecting structures overlooking the ocean. Mass wasting occurs readily along the steep slopes descending to the sea along the emergent coast, especially during the rainy season or where the rocks are weak and/or absorb water. Tsunamis generated by earthquakes in the Pacific basin have struck the California coast many times, some from very distant epicenters.

■ *How do human activities affect coastal hazards?*
Whenever humans modify the natural conditions along the coast, dynamic responses result that can sometimes intensify coastal hazards. For example, although breakwaters can protect one location from wave erosion, they also deflect the energy of approaching waves to other places where erosion increases. When coastal slopes are modified for the construction of roads or buildings, mass wasting can result if the balance between gravity and friction on a table stable slope is compromised. Today, in most coastal communities, awareness of these coastal hazards has led to restrictions on development, but there are still many places where people and property are at risk.

ESSENTIAL TERMS TO KNOW

accretionary terranes, terranes – a large block of rock with characteristics different from surrounding blocks. Terranes are typically bounded by large faults and are thought to represent seamounts, oceanic rises, reefs, island arcs, or other oceanic features accreted to continents at convergent plate boundaries.

alluvium – a general term for sediment transported and deposited by running water.

arête – a narrow jagged ridge separating two glacial valleys or cirques.

basalt – a dark-colored fine-grained igneous rock that forms from magma of mafic (45% to 52% silica) composition.

batholith – a large body of plutonic igneous rock with a surface exposure exceeding 100 square kilometers.

baymouth bar – a spit that extends across the mouth of a bay, closing it off from the open ocean.

blueschist – a foliated metamorphic rock that contains glaucophane, a bluish-colored mineral of the amphibole group.

breccia – a detrital sedimentary rock consisting of angular rock particles larger than 2 millimeters.

caldera – a large circular to oval depression that develops on the summit of a volcano in response to the partial evacuation of the underlying magma chamber.

chert – a fine-grained nonclastic sedimentary rock consisting of microcrystalline quartz, which may include the skeletons of silica-secreting microorganisms such as radiolarian.

cinder cone – a small steep-sided volcano consisting of a loose accumulation of volcanic cinder.

cirque – a generally circular depression that forms in the uppermost reaches of glacial troughs occupied by valley glaciers.

composite volcano – a volcano composed of lava flows, pyroclastic layers, and mudflow deposits; sometimes referred to as a stratovolcano.

dacite – an extrusive igneous rock intermediate in composition between rhyolite and andesite.

diorite – an intrusive igneous rock with nearly equal amounts of dark-colored and light-colored minerals. Diorite is intermediate in composition between granite (felsic) and gabbro (mafic).

emergent coast – a coast where land has risen with respect to sea level.

Farallon plate – an ancient lithospheric plate that separated the North America plate from the Pacific plate during the Mesozoic and Early Cenozoic Eras. Remnants of the Farallon plate include the modern Juan de Fuca, Gorda, Cocos, and Rivera plates in the eastern Pacific Ocean basin.

Farallon subduction zone – the east-dipping zone of subduction developed where the Farallon plate descended beneath the western edge of the North American plate during the Late Mesozoic and Early Cenozoic eras.

fault – a fracture in the Earth's crust that includes displaced rock masses.

felsic – a term describing the composition of magma or igneous rock that contains more than 65% silica and is rich in sodium, potassium, and aluminum.

forearc basin – a basin of sediment accumulation located between a volcanic arc mountain system and an offshore oceanic trench. Forearc basins are developed in association with subduction zones at convergent plate boundaries.

fumerole – a vent at the surface that emits volcanic gases.

gabbro – a dark-colored intrusive igneous rock of mafic composition.

glacial erratic – a rock carried by a glacier from its source to a surface of dissimilar bedrock.

glacial polish – a smooth and glossy bedrock surface produced by the movement of a glacier over it.

glacial striation – a linear scratch or shallow groove on a bedrock surface produced by the movement of a sediment-laden glacier over it.

graben – a term for the block of rock displaced downward as the hanging wall of a normal fault.

granite – a light-colored plutonic igneous rock of felsic composition.

greenstone – a metamorphic rock containing the greenish minerals epidote, chlorite, or amphibole that results from the metamorphism of mafic igneous materials.

headland – land that projects seaward from an irregular shore line.

horn – a steep and jagged peak having the form of a pyramid that developed between glacial cirques.

horst – a term describing the block of rock displaced upward as the footwall of a normal fault.

inverted topography – a term describing any landscape feature that originated at a low elevation, but is currently elevated above the surrounding terrain, or vice versa.

lahar – a volcanic mudflow composed of water, ash, and particles of volcanic rock.

limestone – a chemical sedimentary rock composed of calcite, $CaCO_3$.

lode – an ore deposit in which the valuable commodity is concentrated in a vein or pod within crystalline igneous or metamorphic rock.

mafic – a term describing the composition of magma or igneous rock that contains 45% to 52% silica and is rich in calcium, magnesium, and iron.

mass wasting – the downslope movement of material under the influence of gravity including rockslides, mudslides, rockfalls, and debris flows.

mélange – a deformed and sheared mass of metamorphic and sedimentary rocks that forms in seduction zones.

moraine – a ridge of mound of unsorted and nonstratified glacial sediment (till) deposited by melting glaciers.

mudstone – a fine-grained clastic sedimentary rock consisting of a mixture of sand, silt, and clay-size particles.

normal faults – a dip-slip fault in which the hanging wall has moved down relative to the footwall. Normal faults develop from tensional stress and are most common in areas of divergent plate boundaries

ophiolite – a sequence of mafic igneous rock representing oceanic lithosphere and upper mantle; ophiolites consist of pillow basalt, sheeted basalt dikes, layered and massive gabbro, and mantle periodite.

Pangaea – a supercontinent consisting of all the Earth's landmasses that existed at the end of the Paleozoic Era, about 250 million years ago.

peridotite –an ultramafic igneous rock thought to comprise much of the upper mantle.

physiographic province – a region of unique geology, landforms, drainage, soils, climate, and flora and fauna distinct from adjacent areas on the basis of these features.

pillow structures – rounded or bulbous structures that develop in lava erupted under water.

placer – a term applied to stream-transported sediment such as sand and gravel that contains significant quantities of a valuable mineral such as gold, silver, or platinum.

pluton – an intrusive igneous body that forms when magma cools and crystallizes below the surface and within the crust.

plutonic – a term describing the origin of an igneous rock that crystallized from magma within the crust.

pocket beach– a small beach along an irregular coast located in a recess between projecting headlands.

pyroclastic – a term that describes the fragmental texture or character of volcanic rock such as tuff and volcanic breccia produced during explosive eruptions.

roof pendant – a mass of metamorphic rock preserved above the top of an underlying pluton. Roof pendants represent remnants of the "country rock" into which subterranean magma intruded.

sea arch – an archlike exposure of coastal bedrock that results from wave erosion of sea caves along a projecting headland.

sea stack – a remnant of bedrock on a wave-cut marine terrace.

seismic gap – a portion of an active fault that has produced fewer and smaller earthquakes than other segments of the same fault.

Sierra Nevada batholith – a large composite pluton consisting of more than 100 individual masses of intrusive igneous rock making up the basement of the Sierra Nevada.

serpentinite – a greenish-black metamorphic rock that forms from mafic igneous rocks such as basalt, gabbro, and peridotite. Sepentinite occurs in the western metamorphic terranes of the Sierra Nevada, in the Klamath Mountains, and in the northern Coast Ranges. It is the official California state rock.

spit – a sandy projection of a beach into a body of water such as a bay or estuary.

superterrane – a large fragment of crustal rocks that is comprised of smaller terranes amalgamated during accretion to a continental margin.

syncline – a down-arched or concave-upward fold in a sequence of rock layers. (Note: the above definition is used to conform to that of Monroe, Wincander, and Hazlett)

tombolo – a spit that extends outward into the sea or a lake that connects an island or sea stack to land.

transform plate boundary – a boundary between plates that slide past one another and whose crust is neither produced or destroyed. The strike-slip faults of the San Andreas fault zone represent the transform boundary between the Pacific and North America plates.

triple junction – the point at which three lithosphere plates meet.

tsunami – a large sea wave that is produced when mass on the seafloor is suddenly displaced by earthquakes, volcanic eruptions, or submarine landslides.

tuff – a fine-grained pyroclastic igneous rock that consists of consolidated particles of volcanic ash.

turbidity currents – a dense mixture of sediment and water that flows downslope on the ocean floor.

ultramafic – a term describing the composition of magma or igneous rock that contains 40% or less silica and abundant magnesium and iron.

volcanic – a term describing the origin of igneous rocks from magma that cools rapidly after its eruption during a volcanic event.

volcanic arc – a chain of volcanoes that develops on the earth's surface where magma rises from an underlying subduction zone.

welded tuffs – a hard volcanic rock composed of tiny ash articles that are firmly welded together by the heat associated with an explosive volcanic eruption.

xenoliths – a type of inclusion in which a fragment of older rock is incorporated into younger igneous rock.

MORE ON NORTHERN CALIFORNIA GEOLOGY

California's stunning scenery, rich geologic heritage, and abundant natural resources have stimulated considerable interest from geologists for more than two centuries. Scientific studies in the state have resulted in a vast body of technical literature on California geology. Fortunately, there are many excellent summaries available that describe the geologic features of northern California in comprehensible terms and in the context of modern geologic concepts. Your college or local library may have copies of the following books that you may find valuable in learning more about the geology of northern California:

Assembling California, John McPhee, 2003, Farrar, Straus, and Giroux, New York, 304 pages.

Geology Of California, Deborah R. Harden, 2004, Pearson-Prentice Hall, Upper Saddle River, NJ, 552 pages.

Geology of Northern California, E.H. Bailey, editor, 1966, California Division of Mines and Geology (California Geological Survey) Bulletin 190, 508 pages.

Roadside Geology of Northern and Central Califorina, by David Alt and Donald Hyndman, 2003, Mountain Press Publishing, Missoula, MT, 384 pages.

The California Geological Survey is an excellent source of information on earthquakes, rocks and minerals, geologic hazards, and mapping programs in the Golden State. The Web site at http://www.conservation.ca.gov/cgs contains links to a vast array of information on the geology of California. In addition, the U.S. Geological Survey Web site (http://www.usgs.gov) offers a search feature that allows you to retrieve many USGS publications on specific aspects of California geology, water resources, and geologic hazards.

Finally, check with the geology department at your local college and university about other sources of information and additional opportunities to explore California geology. Most college geology programs offer field courses and introductory lecture courses that address the diverse geologic features of the state.

The *Geology of Northern California* provides an overview of the physiographic features and geological history of northern California's magnificent landscape. Written to accompanying any college-level earth science course, this module explores the rich geological heritage of northern California. The major geological features of the northern Sierra Nevada, the Klamath Mountains, the Cascade Range region, the northern Great Valley, the Basin and Range, and the northern Coast Ranges are explored with an emphasis on applying the fundamental concepts of modern geology to the interpretation of the scenic and varied terrain.

This module also surveys the affect of geological processes on humans in northern California. The origin of the rich mineral and fuel resources of the Golden State are explored in the context of hundreds of million of years of the tectonic evolution. In addition, the multiple hazards to people and property that result from California's on-going geological evolution are considered. We learn why future earthquakes, volcanic eruptions, slope failures, and floods *will* affect northern Californians, and how an understanding of these threats can help reduce their potential impacts.

Use this module to help make any introductory geology course more relevant to college students throughout northern California by providing local and regional examples of the consequences of dynamic geologic processes. Work with your Cengage Learning representative to learn how you can incorporate this or any of the modules from our Regional Geology Series into your course. Visit http://custom.cengage.com/regional_geology/ to learn more about other bonus content available and how to order it.

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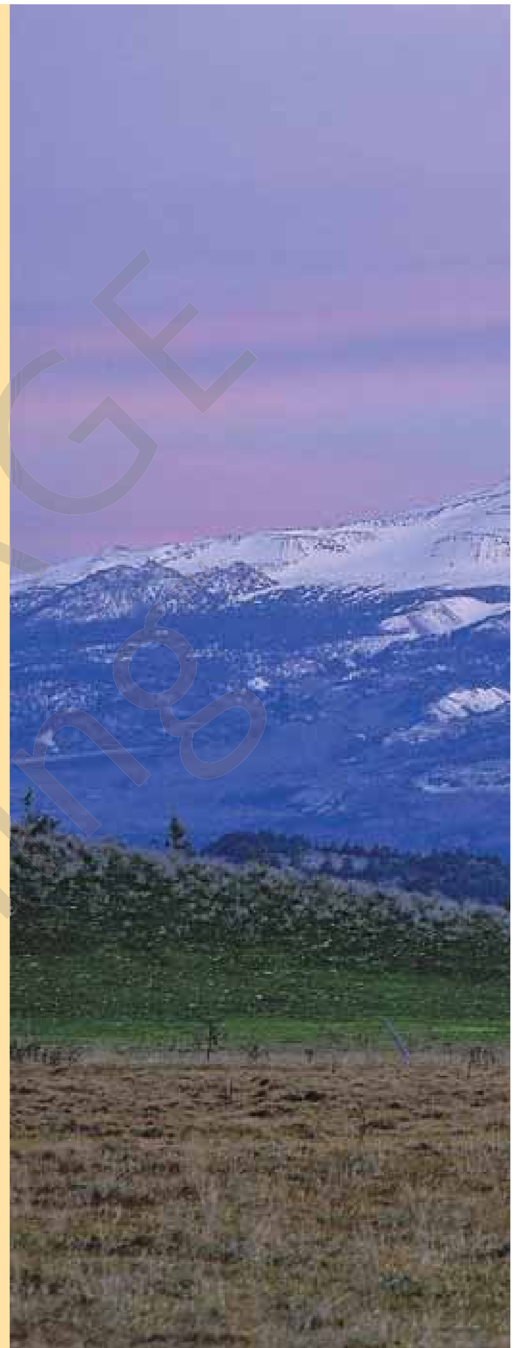

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