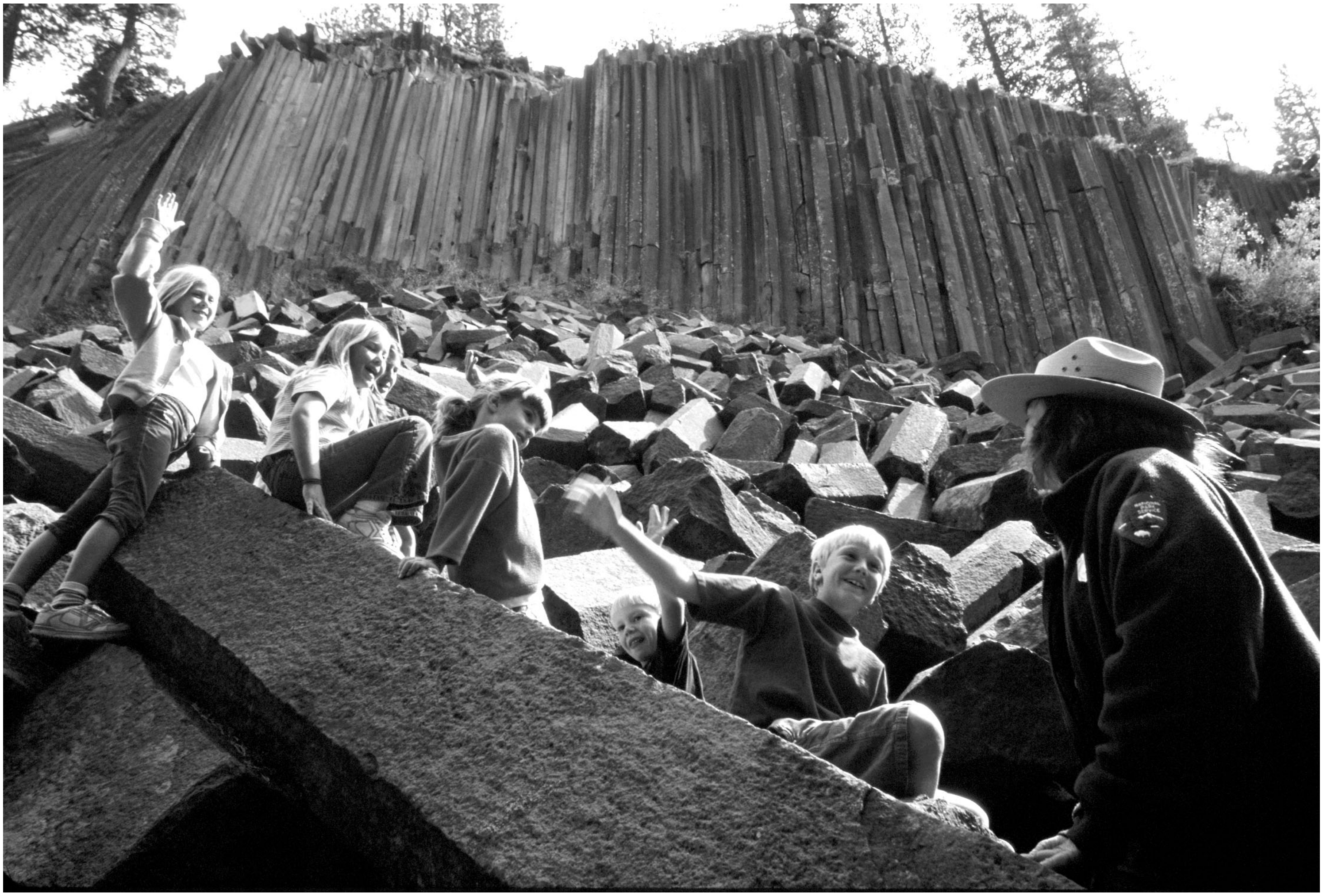
National Park Service
U.S. Department of the Interior

Natural Resource Program Center

Devils Postpile National Monument
Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2009/160



THIS PAGE:
The dramatic columns of Devils Postpile are between 12 and 18 m (40 and 60 ft) tall and up to 1.1 m (3.5 ft) in diameter. Seismic and weathering processes fracture the columns along joints. Broken columns litter the slopes beneath Devils Postpile.

ON THE COVER:
Top view of the 100,000 year-old columns of Devils Postpile. The columns are world-renowned and many form the ideal hexagonal shape. The striations and scratches are evidence that glaciers advanced over the columns, scouring their surface.

National Park Service photographs.

Devils Postpile National Monument

Geologic Resources Inventory Report

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Executive Summary

This report accompanies the digital geologic map for Devils Postpile National Monument in California, which the Geologic Resources Division produced in collaboration with its partners. It contains information relevant to resource management and scientific research. This document incorporates preexisting geologic information and does not include new data or additional fieldwork.

Devils Postpile National Monument, established in 1911, lies southeast of Yosemite National Park in the Sierra Nevada of California. Although a relatively small western national monument, it contains world-renowned examples of vertical columnar basalt. Vertical columns of basalt are rare, requiring homogeneous lava to cool under exceptionally uniform cooling conditions. These columns of basalts—the "posts" for which the Devils Postpile was named—stand 12 to 18 m (40 to 60 ft) high and are up to 1.1 m (3.5 ft) in diameter. They formed 100,000 years ago when lava flowed down the Middle Fork of the San Joaquin River, pooled in the valley, and cooled.

Significant geologic issues at Devils Postpile National Monument include:

- Column collapse
- Preservation of glacial features
- Recurring volcanism

Basalt column collapse is unpredictable, although most of the collapse is likely the result of ground-shaking caused by earthquakes. In 1980, three columns toppled following a series of four intense earthquakes (magnitudes 6.0 or greater on the Richter scale), as well as a swarm of lesser earthquakes that same year. These three columns had been leaning since at least 1909. In addition to ground shaking, the prying action of water that freezes in cracks between the columns may also contribute to column collapse.

Preservation of glacial polish, striations, and grooves on the polygonal tops of the columns provide evidence that Pleistocene alpine glaciers flowed into this area. Rock collecting, which is not permitted in the park, and natural weathering processes have eliminated some of the glacial polish. Removal of these polished tops not only detracts from future visitors' experiences, but also removes critical geologic evidence of glacial processes in Devils Postpile National Monument.

Hot springs, seismic activity, and carbon dioxide gas emissions suggest that the volcanoes in this region are not extinct. Active seismicity and ground deformation characterize the Long Valley Caldera that lies northeast of Devils Postpile National Monument. Future volcanic activity may produce small- to moderate-volume pyroclastic eruptions, cinder cones, and lava flows.

Not all of the basalt columns are vertical. Because vertical columns require exceptionally uniform cooling conditions in homogeneous flows, many columns in the monument are tilted, and some display spectacular curved shapes.

In addition to the basalt of Devils Postpile, other volcanic features are present in the monument area. The Buttresses, a feature composed of the oldest volcanic unit in the park, resulted from lava that erupted from vents west of Devils Postpile National Monument. A lava flow composed of the volcanic rock rhyodacite is responsible for the cliff at Rainbow Falls, a 31-m (101-ft) waterfall and the highest waterfall on the Middle Fork of the San Joaquin River. Dense hard volcanic tuff from the catastrophic eruption that produced the 16- by 32-km (10- by 20-mi) Long Valley Caldera is exposed behind the old ranger cabin east of Reds Meadow. Remains of a 10,000-year-old basalt flow and cinder cones are preserved at Red Cones, about 2.4 km (1.5 mi) southeast of Devils Postpile National Monument.

When tectonic forces uplifted the Sierra Nevada in the Quaternary, the mountains were simultaneously being worn down by Pleistocene glaciation. Glaciers flowed down the Middle Fork several times, gouging out a U-shaped valley and leaving their marks on the rocks. Glacial polish, striations, and grooves are evidence of the erosive power of the glaciers. "Glacial erratics," boulders carried by the glaciers, are strewn throughout the region and are most abundant on the high granite hills and ridges west of the Middle Fork. Glacially-carved cirque basins contain alpine lakes at the base of glacially-shaped peaks.

Rocks in the Sierra Nevada record a history of tectonic change that occurred along the western margin of North America beginning as far back as the Paleozoic Era. Plutonic, volcanic, and sedimentary rocks were deformed and added to the continental margin as the North American continent overrode subducting slabs of oceanic lithosphere. In the Cenozoic, transpression (plates colliding and sliding past each other) and strike-slip faulting (plates sliding past each other) generated the San Andreas Fault system. High heat flow continues to uplift the region today. Mineral springs, earthquakes, and volcanic activity that occurred as recently as 600 years ago attest to the continued tectonic activity in the Devils Postpile region.

The glossary contains explanations of many technical terms used in this report, including the Map Unit Properties Table.

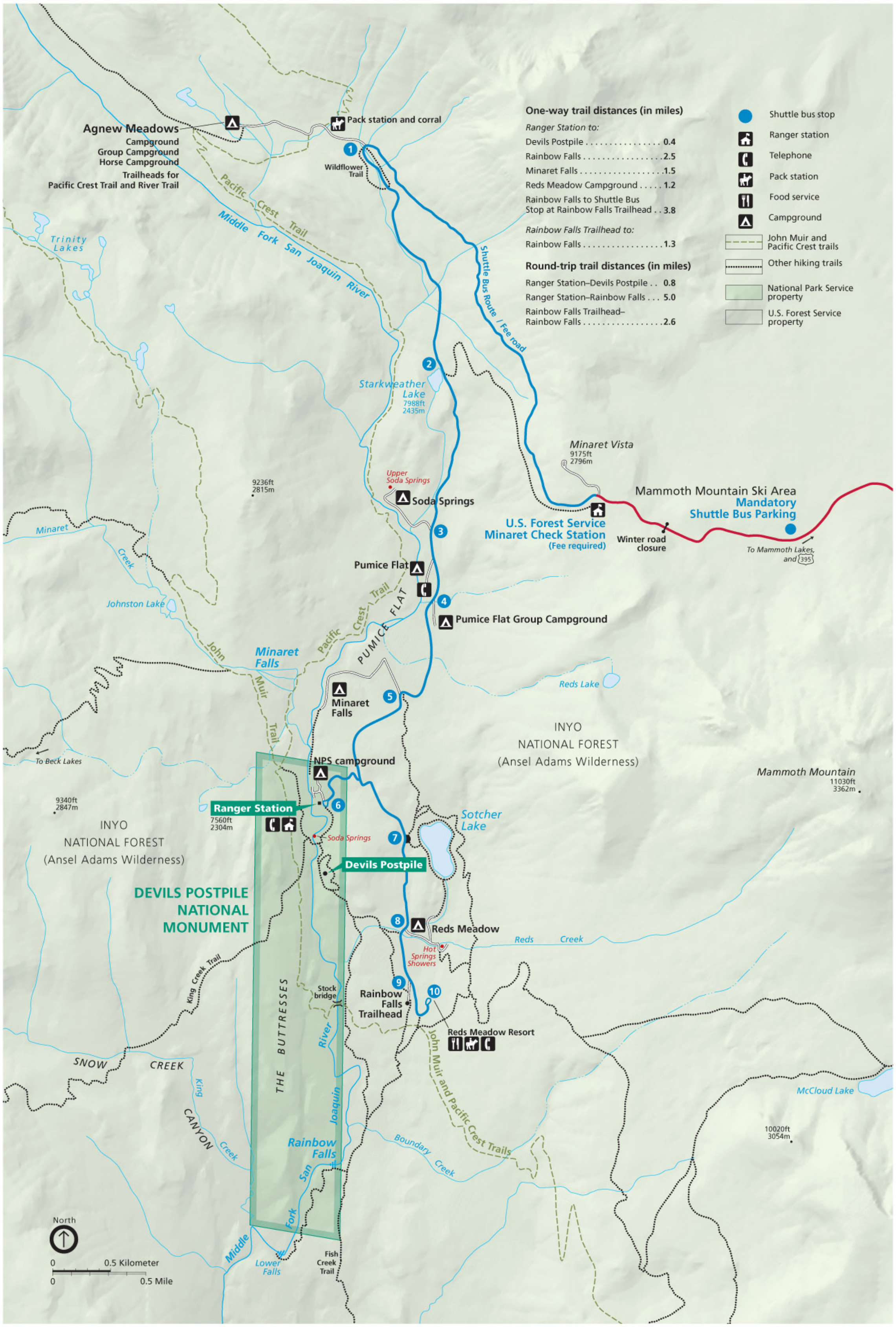


Figure 1. Location map of Devils Postpile National Monument. National Park Service map.

Introduction

The following section briefly describes the National Park Service Geologic Resources Inventory and the regional geologic setting of Devils Postpile National Monument.

Purpose of the Geologic Resources Inventory

The Geologic Resources Inventory (GRI) is one of 12 inventories funded under the National Park Service (NPS) Natural Resource Challenge designed to enhance baseline information available to park managers. The program carries out the geologic component of the inventory effort. The Geologic Resources Division of the Natural Resource Program Center administers this program. The GRI team relies heavily on partnerships with the U.S. Geological Survey, Colorado State University, state surveys, and others in developing GRI products.

The goal of the GRI is to increase understanding of the geologic processes at work in parks and provide sound geologic information for use in park decision making. Sound park stewardship relies on understanding natural resources and their role in the ecosystem. Geology is the foundation of park ecosystems. The compilation and use of natural resource information by park managers is called for in section 204 of the National Parks Omnibus Management Act of 1998 and in NPS-75, Natural Resources Inventory and Monitoring Guideline.

To realize this goal, the GRI team is systematically conducting a scoping meeting for each of the identified 270 natural area parks and providing a park-specific digital geologic map and geologic report. These products support the stewardship of park resources and are designed for nongeoscientists. Scoping meetings bring together park staff and geologic experts to review available geologic maps and discuss specific geologic issues, features, and processes.

The GRI mapping team converts the geologic maps identified for park use at the scoping meeting into digital geologic data in accordance with their innovative Geographic Information Systems (GIS) Data Model. These digital data sets bring an exciting interactive dimension to traditional paper maps by providing geologic data for use in park GIS and facilitating the incorporation of geologic considerations into a wide range of resource management applications. The newest maps come complete with interactive help files. This geologic report aids in the use of the map and provides park managers with an overview of park geology and geologic resource management issues.

For additional information regarding the content of this report and current GRI contact information please refer to the Geologic Resources Inventory Web site (http://www.nature.nps.gov/geology/inventory/).

Regional Location and Geologic Setting

At 323.13 ha (798.46 ac), Devils Postpile is a relatively small national monuments in the western United States (fig. 1). The monument lies within California's Sierra Nevada, the largest fault-block mountain range in the United States (fig. 2). Rising sharply on its eastern side from the Great Basin, the Sierra Nevada forms an asymmetric mountain range with a western slope that descends gradually to near sea level. The mountain range is 645 km (400 mi) long, 65 to 130 km (40 to 80 mi) wide, and contains eleven peaks that rise to more than 4,270 m (14,000 ft) above sea level.

The monument is located approximately 17 km (11 miles) southeast of Yosemite National Park near the escarpment that defines the eastern edge of the Sierra Nevada fault block. The Middle Fork of the San Joaquin River flows south through Devils Postpile National Monument and then angles west to flow across the Sierra Nevada and into the Great Valley of California near Fresno.

Devils Postpile National Monument contains rare geologic features—polygonal columns of Quaternary basalt, the "posts" for which the monument is named (fig. 3). The origin of these great pillars mystified early observers, with some surmising that the lava had "plunged over a precipice, split into prisms, and hardened in mid air!" (Huber and Eckhardt 2002).

In addition to the basalt columns, Quaternary (2.6 million years ago to the present) extrusive volcanic rocks and Cretaceous (145.5 to 65.5 million years ago) intrusive igneous rocks form the landscape of Devils Postpile National Monument (fig. 4). These rocks range in composition from granodiorite to leucogranites (granites rich in potassium feldspar and aluminum). Rock units mapped in the vicinity of the Devils Postpile and in Yosemite National Park include metamorphosed Paleozoic rocks, Jurassic and Triassic volcanic deposits, and Jurassic and Triassic sedimentary rocks (Huber and Rinehart 1965; Huber 1987).

Glaciers flowed down the valley of the Middle Fork of the San Joaquin River during the Pleistocene and eroded most of the lava flows from the area. The glaciers cut a vertical face on a remnant of the lava flow that became the Devils Postpile, and exposed the interior of the flow and the sides of the columns. Today, effects of glaciation can be seen in the glacial polish and striations on the top of the Devils Postpile and in "glacial erratics" (boulders deposited some distance from their point of origin) scattered throughout the monument.

Formation of the Devils Postpile

The 12- to 18-m (40- to 60-ft) high columnar basalt of the Devils Postpile ranks as one of the world's finest examples of columnar basalt (fig. 3). About 100,000 years ago, a volcano erupted north of Pumice Flat and filled the valley of the Middle Fork of the San Joaquin River with runny basaltic lava. The lava flowed at least 5 km (3 mi) downstream and accumulated in the vicinity of the Devils Postpile to an exceptional depth of approximately 122 m (400 ft) (Huber and Eckhardt 2002). The basaltic lava was very fluid and remained molten while it pooled in the valley behind a natural dam (e.g., a glacial moraine). To form columns that are so much longer than those formed from a typical basalt flow, the lava behind the natural dam had to be remarkably deep. After the lava solidified, glacial erosion removed approximately half of the flow, leaving the thick center exposed (Allen Glazner, University of North Carolina, written communication, June 10, 2009).

The top and bottom of the lava cooled and solidified rapidly because of exposure to air and cooler granite bedrock. As the solidifying lava cooled from the outside surfaces inward, it also shrank, as do virtually all liquids when frozen or solidified. With shrinkage, tensional stresses developed in the lava. The column formation is summarized as follows (Huber and Eckhardt 2002):

- Surface cracks developed when the tension caused by the shrinkage of cooling was greater than the strength of the lava.
- As cracks reached about 25 cm (10 in), they branched to form a Y-shape with equal angles of approximately 120 degrees around all sides, an angle that provides the greatest stress relief.
- Each new crack branched again when it reached the critical length, and together with other similar cracks formed an irregular polygonal pattern.

To form exceptionally long, uniform, vertical columns, a lava flow must be of uniform thickness, be homogeneous in chemical composition, and have level top and bottom cooling surfaces. Irregularities in chemical composition or thickness result in tilted or curved columns. Columns exhibiting extreme curvatures formed adjacent to the rare vertical columns at Devils Postpile National Monument (fig. 3).

Park History

Although early American Indians camped in and frequently visited this region, they left no record of their observations of the columns of basalt (Kiver and Harris 1999). Local hermits (e.g., Red Sotcher and Tom Agnew), as well as early miners, must also have known about the striking columns, but they also left no written records. Locally, the area was known as the Devils Woodpile.

When Yosemite National Park was established in 1890, its boundaries were more extensive than they are today and encompassed the Devils Postpile. Pressure was applied immediately by the timber and mining industries to reduce the park's boundaries. The first park superintendents were military officers, and many of them recommended that the southeast part of Yosemite be returned to public domain and the resources exploited. But in 1895, Captain Alex Rodgers noted that the Devils Postpile was justification in itself to maintain park status. Although recognition of the importance of the Devils Postpile grew, in 1905, Congress removed 1,300 sq km (500 sq mi), including Devils Postpile, from Yosemite National Park. Newspaper articles about the Devils Postpile attracted public attention, while intense mineral exploration began in the former parklands. Subsequnt decades of mineral exploration determined that the area was barren of valuable mineral deposits.

In 1910, Walter Huber, the district engineer for the U.S. Forest Service, received an application from a mining company to blast the Devils Postpile and use the rock for the core of a hydroelectric dam on the Middle Fork of the San Joaquin River. Huber, John Muir, and other members of the newly formed Sierra Club were opposed to this plan. A letter writing campaign to officials in Washington led to President William Howard Taft designating the area as Devils Postpile National Monument on July 6, 1911.

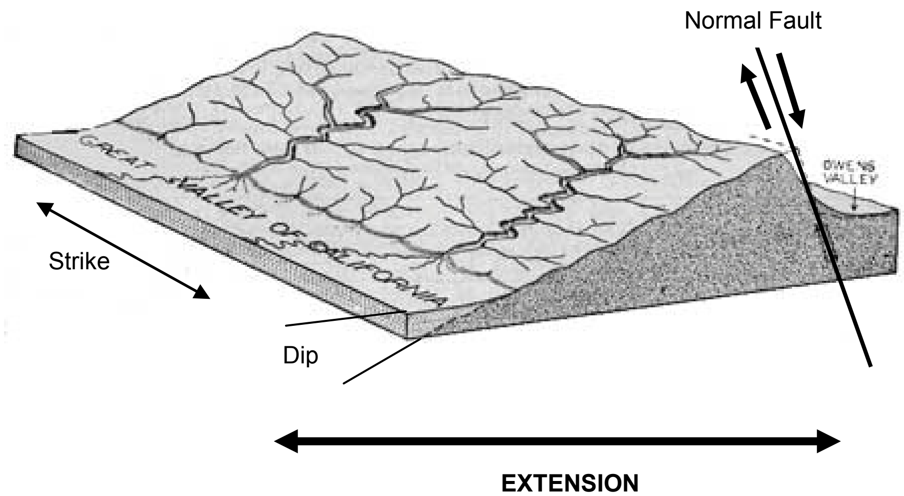


Figure 2. The Sierra Nevada fault block. The historic view of the Sierra Nevada shows the great eastern escarpment that rises nearly 3 km (2 mi) from Owens Valley (foreground). The generalized diagram illustrates the origin of the Sierra Nevada fault block. As tectonic forces pulled apart the region (Basin- and- Range extension), the Sierra Nevada was tilted upwards (relative to the Owens Valley block) along a basin-bounding normal fault. The “dip” of the beds is the angle the beds make with the surface, while the “strike” represents the compass direction that the inclined beds make when they intersect the surface. For an explanation of the various types of faults, see figure 17. Both the photograph and diagram are from Matthes (1930). The photograph is also available online from the U.S. Geological Survey photographic library at: http://libraryphoto.cr.usgs.gov/htmllib/btch432/btch432j/btch432z/mwc01116.jpg. The diagram is available online at: http://www.nps.gov/history/history/online_books/geology/publications/pp/160/sec2a.htm. Both accessed November 2009.

Figure 3. Basalt columns of the Devils Postpile. Uniform composition and thickness resulted in exceptionally long, vertical columns (about 20 m or 60 ft long). Differences in composition, thickness, cooling rates, and other irregularities produced the curved columns to the left of the vertical columns. Column collapse has created a talus pile at the base of the columns. National Park Service photograph, available at: http://www.nps.gov/depo/photosmultimedia/photogallery.htm. Accessed November 2009.

Era	Period	Rock Unit		Explanation
CENOZOIC	Quaternary		Undifferentiated surface deposits	Includes pumice, stream deposits, and recent organic soils.
			Basalt of the Red Cones	Unglaciated red cinder cones and lava flows.
		Andesite of the Devils Postpile	Basalt of the Devils Postpile	Dark- gray, fine- grained basalt flow. Contains abundant feldspar crystals.
			Andesite of Mammoth Pass	Gray, fine- grained andesite. Minor feldspar and pyroxene crystals.
			Rhyodacite of Rainbow Falls	Light- gray, fine- grained rhyodacite. Exhibits horizontal weathering fractures. Some dense, black, columnar-jointed outcrops.
			Tuff of Reds Meadow	Buff, ash-flow rhyolite. Welded pumice with abundant quartz, feldspar, and rock fragments.
		Andesite of the Devils Postpile	Basalt of the Buttresses	Dark- gray basalt. Abundant olivine crystals and pyroxene. Crude columnar jointing.
	Regional Unconformity (time gap of at least 83 million years)			
MESOZOIC	Cretaceous	Granite and Granodiorite similar to the Cathedral Peak Granite in Yosemite National Park		Coarse- grained plutonic igneous rock with abundant light-colored crystals of quartz and feldspar and minor amounts of dark-colored crystals, chiefly biotite. Commonly contains blocky crystals (phenocrysts) of potassium feldspar up to 5 cm (2 in) long.
		Mount Givens Granodiorite		Medium- grained plutonic igneous rock composed of quartz, potassium feldspar, plagioclase, and the dark-colored minerals, biotite and hornblende.

Figure 4. General stratigraphic column showing rock units exposed in Devils Postpile National Monument and within 1.6 km (1 mi) of the monument's boundaries. Huber and Rinehart (1965) combined the four volcanic units shaded in orange into the "Andesite of the Devils Postpile" (Attachment 1). Compiled from Huber and Rinehart (1965) and Clow and Collum (1983). Refer to the Map Unit Properties Table for more detailed information.

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping session for Devils Postpile National Monument on September 25-26, 2002, to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. This section synthesizes the scoping results, in particular those issues that may require attention from resource managers.

Issues in this section are identified in relative order of resource management significance, with the most critical discussed first. Potential research projects and topics of scientific interest are presented at the end of this section.

The geologic issues section addresses geologic issues as they affect the ecosystem, their importance to park management, and the extent to which they are anthropogenically influenced. At Devils Postpile National Monument, the primary geologic issue is the potential collapse of the basalt columns. Contact the Geologic Resources Division for technical assistance.

Column Collapse

In the 10,000 to 12,000 years since the last glaciers flowed down the valley of the Middle Fork, numerous columns have fallen from the face of the cliff, creating a talus pile of broken columns (fig. 3). Earthquakes and the persistent freeze-thaw weathering process in the area could topple the vertical columns in Devils Postpile National Monument, although the present rate of column collapse is sporadic and not well understood.

Earthquakes are likely the principal triggering mechanism behind column collapse in the park (Dr. Greg Stock, geologist, Yosemite National Park, written communication, July 27, 2009). Ground- shaking from earthquake activity in 1980 may be responsible for the collapse of three leaning columns that had been separated from nearby vertical columns by as much as 0.3 m (1 ft) since 1909 (Huber and Eckhardt 2002; Kiver and Harris 1999).

From May 25 to 27, 1980, intense earthquake swarms occurred at an epicenter about 3 km (2 mi) southeast of Mammoth Lakes, California (fig. 5). Four earthquakes with magnitudes of 6.0 or greater on the Richter scale (along with more than 200 aftershocks of magnitude 3.0 or greater) shook this eastern Sierra community (Archuleta et al. 1982; Harp et al. 1984). These earthquakes triggered several thousand landslides throughout an area of approximately 2,500 sq km (970 sq mi), ranging as far west as Yosemite Valley (Harp et al. 1984). Lesser earthquake swarms accompanied by sporadic tremors continued throughout the summer of 1980, and on July 7, 1980, the three leaning columns fell.

The earthquake activity in 1980 resulted in the cracking of other columns, which currently rest precariously on their severed bases. Presumably weakened by small earthquakes, columns in the area continue to fall at an unpredictable rate. Mammoth Lakes continues to be seismically active. For example, from November 3 to November 11, 2009, 24 earthquakes with magnitudes ranging from 0.1 to 1.5 occurred within a 16-km (10-mi) radius of Mammoth Lakes (http://quake.wr.usgs.gov/recenteqs/FaultMaps/Long_Valley_eqs.htm, accessed November 2009). Significant earthquakes that might knock down columns also occur along the California—Nevada border, northeast and southwest of the Devils Postpile (fig. 6).

The prying action of water freezing in the cracks between the columns may also trigger column collapse. Ice expansion is a slow process, but over time, columns may be pried apart, lean, and eventually tumble under the pull of gravity. Other processes that might destabilize the columns include the prying affect of roots growing in fractures and joints and other biological activity.

Preservation of Glacial Features

It is likely that, at one time, nearly all of the upper surfaces of exposed rock in Devils Postpile National Monument exhibited glacial polish and glacial striations from the last ice age. Weathering and subsequent erosion have removed almost all of the original polished surfaces. Only patches of polished surfaces remain, such as those on top of the Devils Postpile (fig. 7). Because these polished surfaces and striations document the presence of glaciers in Devils Postpile National Monument, the regulation prohibiting collection of this material is especially important. Unsuspecting collectors could remove the evidence that glaciers sheared off the top of the Devils Postpile, destroying scientific evidence and also limiting future visitors' enjoyment and understanding of the area (Huber and Eckhardt 2002).

Recurring Volcanism

Several phenomena provide dramatic evidence that volcanoes in this region are not extinct: trees dead from carbon dioxide gas emanating from the south flank of Mammoth Mountain near Horseshoe Lake; swarms of earthquakes in the 1980s and 1990s; relatively young and widespread pumice deposits; and numerous hot springs such as those at Reds Meadow approximately 0.8 km (0.5 mi) east of the monument (Huber and Eckhardt 2002). Active seismicity and ground deformation suggests that the Long Valley Caldera remains restless. The 15- by 30- km (9- by 18- mi) Long Valley Caldera, formed during an eruption about 760,000 years ago, lies northeast of Devils Postpile National Monument (fig. 8). Mammoth Mountain, a dome complex on the southwestern rim of the caldera, erupted approximately 67,000 years ago (Mahood et al. 2000).

Calderas are cauldron-shaped volcanic features that are sometimes confused with volcanic craters. Volcanic craters form circular vents from which magma erupts as lava, gases, and ejecta. During exceptionally catastrophic eruptions, the magma chamber may empty enough so that the land above the chamber collapses, forming a caldera (e.g., Yellowstone National Park).

Eruptions in the Long Valley Caldera region produce both higher-viscosity silicic (felsic) and lower-viscosity mafic lavas. Silicic lavas are rich in silica and typically form the lighter-colored volcanic rock rhyolite. Dark-colored minerals rich in iron and magnesium compose mafic lavas that typically form andesite and basalt, darker-colored volcanic rocks. Mafic and silicic lavas erupted contemporaneously in four sequences over the past 160,000 years (Mahood et al. 2000):

1. the western moat sequence (~160,000 years ago);
2. the Mammoth sequence (~119,000 to 57,000 years ago);
3. the northwest caldera sequence (~40,000 to 29,000 years ago); and
4. the Inyo chain sequence (~1,400 years ago to the present).

About 550 years ago, a series of explosive magmatic and phreatic eruptions and emplacement of lava flows occurred at several vents at the Inyo volcanoes (Miller 1989). Small eruptions occurred about 250 years ago in Mono Lake at the north end of the Mono-Inyo Craters volcanic chain. Magmatic eruptions extrude molten or partially molten rock material, while phreatic eruptions involve steam, mud, or other material that is not incandescent. Phreatic eruptions result from the heating and consequent expansion of groundwater due to an underlying igneous heat source.

The Long Valley Observatory, one of five U.S. Geological Survey Volcano Observatories that monitor volcanoes within the United States, monitors and studies geologic unrest in and around the Long Valley Caldera—including earthquakes, ground deformation, and degassing activity (http://volcanoes.usgs.gov/lvostatus.php , accessed November 2009). The most likely potential hazard from volcanic activity in the Mono Lake—Long Valley area will come from both silicic and mafic magma eruptions (Miller 1989). Silicic eruptions in the Mono Lake—Long Valley area are expected to produce small- to moderate- volume pyroclastic eruptions that will form pyroclastic flows, and small- to moderate- amounts of tephra (volcanic material ejected from the vent, such as ash and rock fragments). Mafic eruptions will form cinder cones, small volumes of tephra, lava flows, and some phreatic explosions.

Potential Research Projects

Research projects proposed during the scoping meeting include:

- Dating lava flows
- Monitoring glacial polish
- Monitoring column stability
- Groundwater chemistry of springs in the meadow
- Carbon dioxide flow in the soil, and possible tree kill
- Hydrology/geomorphology of the San Joaquin River
- Global climate change relative to species diversity
- Historic flows of the San Joaquin River
- Possible effects to Devils Postpile National Monument springs and watershed from proposed groundwater pumping on San Joaquin ridge.

The NPS Water Resources Division should be consulted with regard to surface water and groundwater projects.

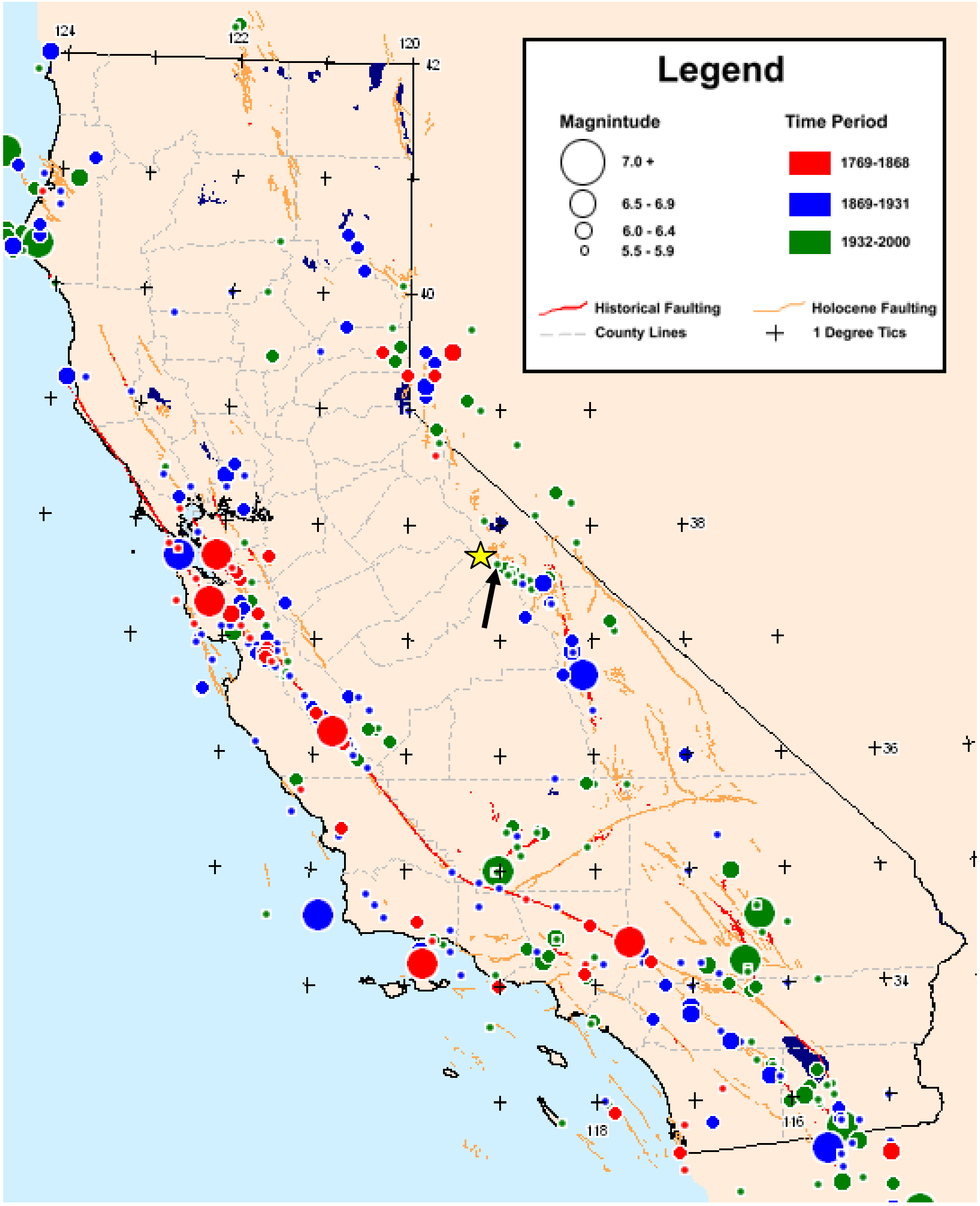


Figure 5. Historical earthquake map of California. The yellow star (not to scale) represents the approximate location of Devils Postpile National Monument. The arrow points to the location of the 1980 earthquakes near Mammoth Lakes, California. Modified from California Geological Survey graphic, available at: http://redirect.conservation.ca.gov/cgs/rghm/quakes/historical/index.htm. Accessed November 2009.

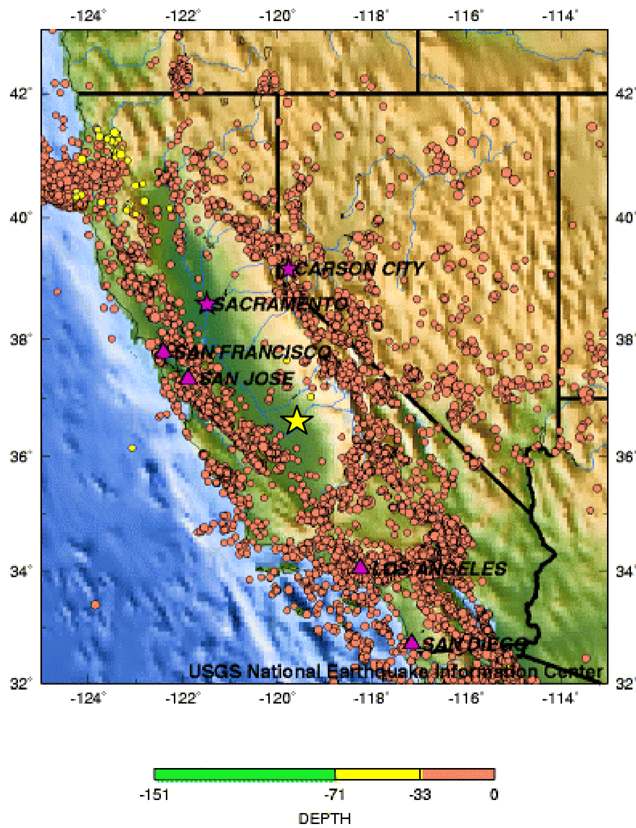


Figure 6. Seismicity of California showing earthquakes from 1990 to 2006. The colored circles designate earthquake locations, with the various colors indicating depth ranges in kilometers (see depth key above). Note that most of the earthquakes have occurred within 33 km (21 mi) of the surface. Purple triangles depict cities and purple stars depict state capitols. The yellow star (not to scale) represents the approximate location of Devils Postpile National Monument. Modified from U.S. Geological Survey graphic , available at: http://earthquake.usgs.gov/regional/states/california/seismicity.php. Accessed November 2009.

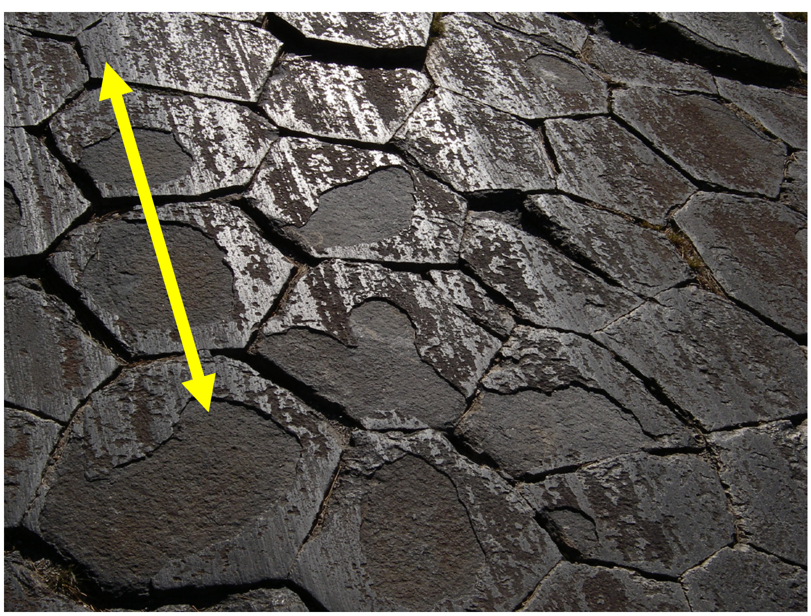


Figure 7. Glacial polish and glacial striations (parallel scratches or lines) on the top of the columns at Devils Postpile National Monument. Glacial abrasion caused both features. Due to weathering or illegal collecting, some of the glacial polish has been removed from the polygonal tops of the Postpile. Striations provide directional evidence, as well. In this picture, the last glacier followed one of two directions, as indicated by the yellow arrow. Modified from a National Park Service photograph by David Scott, available at: http://www.nps.gov/depo/photosmultimedia/photogallery.htm. Accessed November 2009.

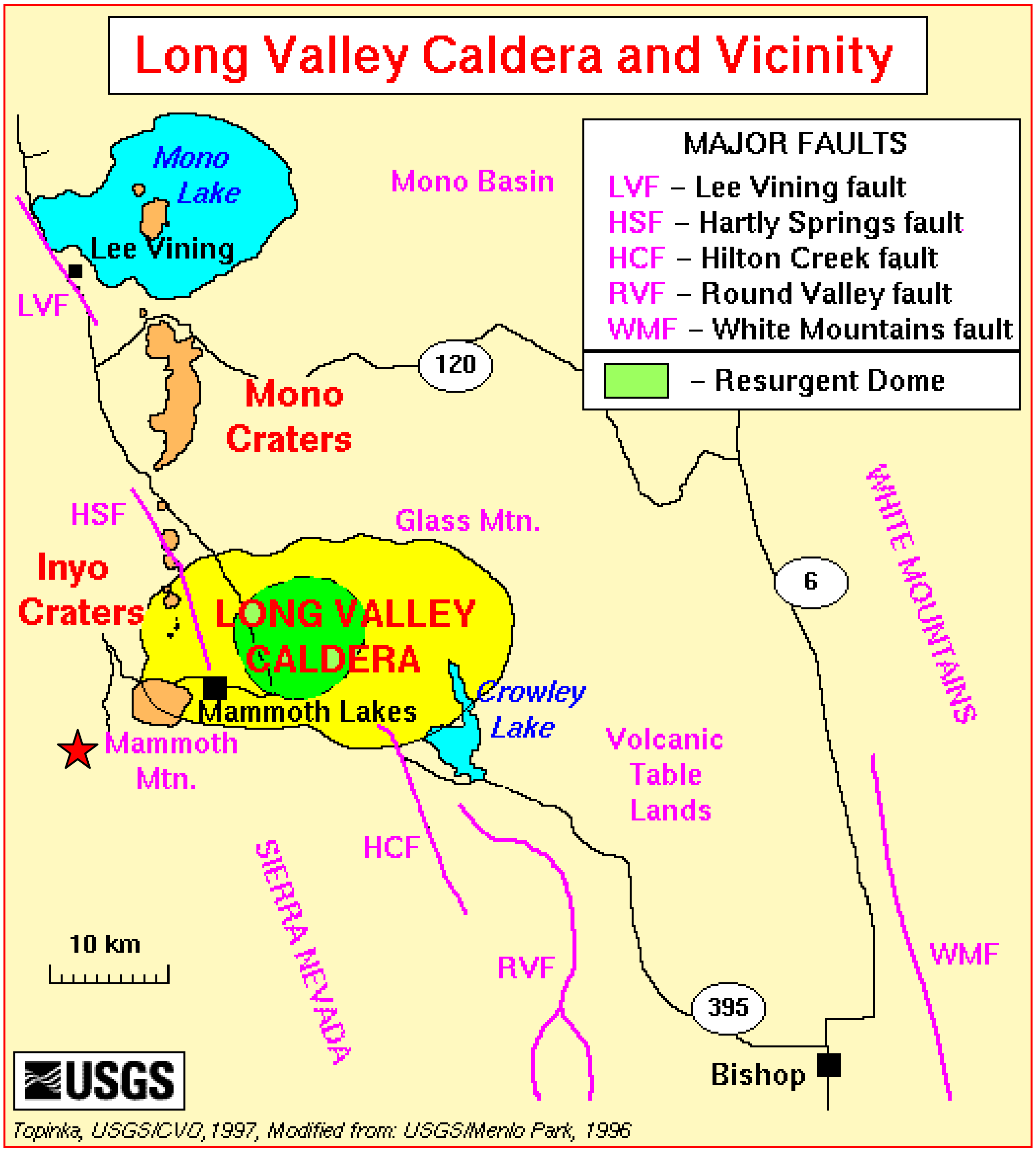


Figure 8. Long Valley Caldera and vicinity. Seismic unrest occurs in the Mono Lake – Long Valley area on a regular basis, and is monitored by the Long Valley Observatory. The red star (not to scale) represents the approximate location of Devils Postpile National Monument. Modified from U.S. Geological Survey graphic, available at: http://vulcan.wr.usgs.gov/Volcanoes/LongValley/Maps/map_long_valley.html. Accessed November 2009.

Figure 9. Exposed ends of the columns at Devils Postpile National Monument showing the polygonal patterns. Note the hexagonal shape of the columns. National Park Service photograph, available at: http://www.nps.gov/depo/photosmultimedia/photogallery.htm. Accessed November 2009.

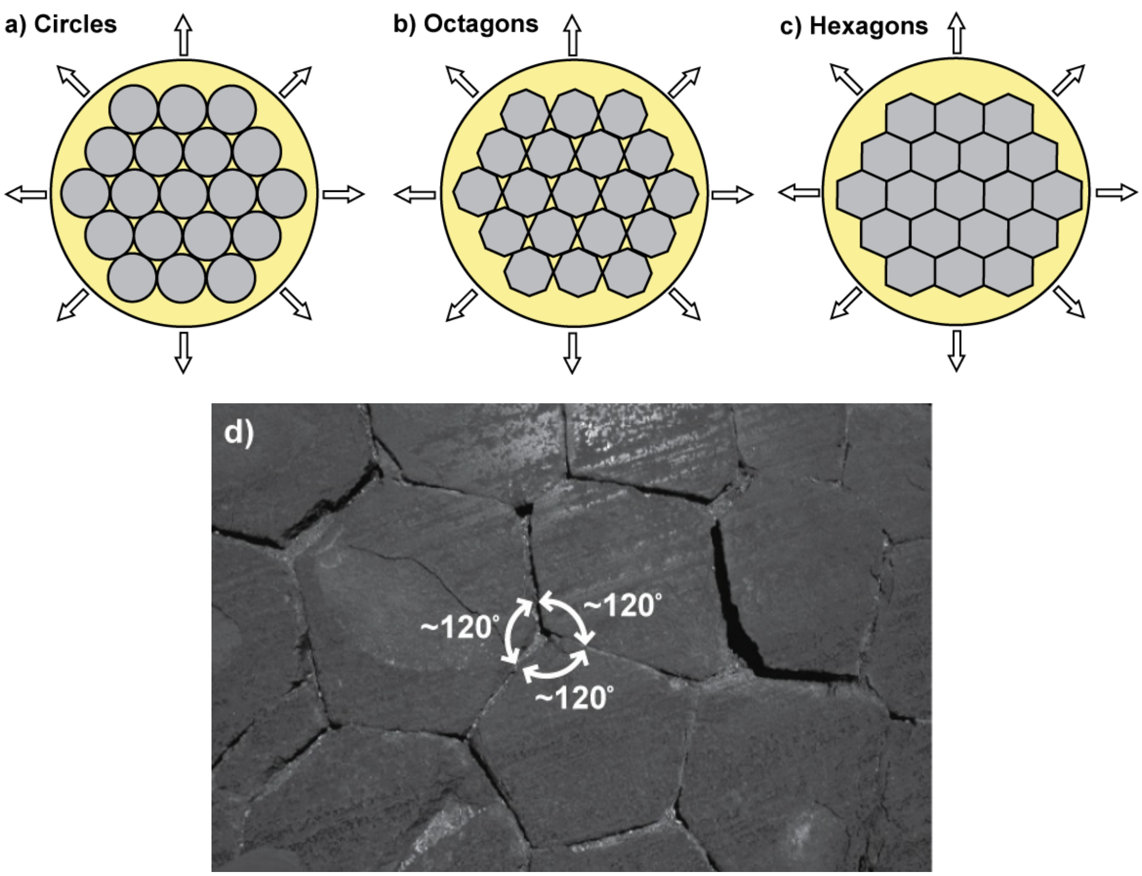


Figure 10. A hexagonal pattern is the ideal shape for columnar joints in basalt. If homogenous lava cools uniformly, it shrinks and is subject to tensional forces (white arrows) that are equal in all directions. Compared to circles (a) and octagons (b), the hexagon (c) fits most efficiently without gaps. The columnar joints at Devils Postpile NM have a large proportion of hexagonal columns, which is rare. Not all columns are hexagonal because lava is not completely homogeneous and does not cool perfectly uniformly. As shown in (d), some columns are also 5-sided with joints intersecting at nearly 120-degree angles. Graphics and photograph modified from Lillie (2005), used with permission.

Geologic Features and Processes

This section describes the most prominent and distinctive geologic features and processes in Devils Postpile National Monument.

Features exposed in Devils Postpile National Monument owe their origin to both fire and ice. Volcanic eruptions, igneous intrusions, and mountain-building processes tied to the tectonically active margin of western North America created the raw material from which Pleistocene glaciers carved the park's distinct landscape. Today, the Middle Fork of the San Joaquin River meanders through a glacially-carved valley that once supported a river of ice. This high-Sierran river corridor sustains healthy forests and lush sub-alpine meadows.

Devils Postpile

The world-renowned columnar jointing at Devils Postpile National Monument formed from a lake of lava up to 122 m (400 ft) deep and at least 5 km (3 mi) long. A single lava flow is rarely this thick. The vertical columns of the Devils Postpile represent an extraordinary occurrence in which uniform cooling conditions in a compositionally homogeneous lava produced uniform shrinkage. As the lava cooled and shrank, brittle fractures started forming that allowed the basalt to crack into long, vertical columns. The basalt columns at the Devils Postpile have a maximum diameter of 1.1 m (3.5 ft) and measure up to 18 m (60 ft) long (fig. 3).

The most efficient way to relieve contraction stress is by means of three fractures radiating in a Y-shape, separated by angles of 120 degrees. The merger of these cracks creates hexagonal polygons (figs. 9 and 10). If conditions were perfect and constant, all such columns would be six-sided (Huber and Eckhardt 2002). However, regular hexagonal polygons are atypical because cooling stresses in natural lava flows are never completely uniform (Huber and Eckhardt 2002; http://geomaps.wr.usgs.gov/parks/depo/dpgeol1.html, accessed November 2009). Thus, the columns at Devils Postpile are bounded by curved cracks forming irregular-shaped polygons with variable numbers of sides. In a study of 200 posts, 55% of the columns were six-sided, 37% were five-sided, 5% were seven-sided, and 2% were four sided (Huber and Eckhardt 2002; Kiver and Harris 1999).

With 55% hexagonal polygons, Devils Postpile National Monument proves exceptional. By comparison with other well-known columnar features, hexagonal polygons border 51% of the columns at Giant's Causeway in Northern Ireland, 32.5% of the columns at Devils Tower National Monument in Wyoming, and 16% of the columns at Craters of the Moon National Monument in Idaho (Huber and Eckhardt 2002).

Perpendicular columns depend on a relatively horizontal ground surface, uniform cooling conditions, and homogeneous composition. At the Devils Postpile, however, many columns diverge from the vertical. Some appear tilted and some display spectacular curved shapes (fig. 3). Features and phenomena that may have influenced cooling rates and led to curved columnar joints include buried hills and valleys, irregular surfaces in lava flows, filled lava channels and lava tubes, rain or water contacting the lava, and compositional differences in the lava.

At Devils Postpile National Monument, the lava columns extended many feet in front of the present face after the last glacier melted. Sporadic collapse of the columns over the years has left a large talus pile of broken posts at the base of the current Devils Postpile (fig. 3).

Glacial Features

Numerous episodes of Pleistocene glaciation carved the jagged peaks and U-shaped valleys of today's Sierra Nevada (Kiver and Harris 1999). The alpine glacier that flowed down the Middle Fork of the San Joaquin River scoured and scraped away most of the Devils Postpile lava flow about 10,000 to 12,000 years ago. The river of ice eroded most of the lava flows in the area, but left some remnants of the original lava flows. The glacier cut a vertical face on the remnant known as the Devils Postpile, exposing the interior of the flow and the sides of the columns (fig. 3).

The top of the Devils Postpile reveals not only a cross section of the polygonal pattern of the posts, but also the polished and scoured effects of flowing ice (fig. 7). As the glacier flowed down the valley, fine silt that was embedded in the ice acted as nature's scouring pad and polished the ends of the columns. Pebbles, boulders, and other coarse debris scraped across the columns, producing parallel striations and grooves in the basalt.

Rounded bedrock exposures within and near the monument that have one steep slope and one gentle slope indicate the direction of ice flow. Glaciers flowing over fractured bedrock tend to pry and pluck blocks of jointed rock away from the downstream side of the outcrop. On the upstream side, abrasive material within the glacier polishes and smoothes the bedrock surface. Plucking action on the downstream side of the rock outcrop creates a steep slope while the polishing action of ice forms a gentle slope that faces upstream. Such a glacial feature is called a "roche moutonnée." Pothole Dome on the west side of Tuolumne Meadows in Yosemite National Park is an excellent example of a roche moutonnée (fig. 11) (Huber 1987).

Glaciers also carried large boulders (glacial erratics) from points upstream and deposited them when the glaciers melted. Many of the glacial erratics in the Devils Postpile area consist of metamorphic rock that only occurs north of the monument. Glacial erratics are most abundant on the high granite hills and ridges west of the Middle Fork of the San Joaquin River (http://geomaps.wr.usgs.gov/parks/depo/dpgeol1.html, accessed November 2009). Yosemite National Park, northwest of Devils Postpile, contains many excellent geologic features that have resulted from alpine glaciation—including horn-shaped peaks, cirque basins, moraines, glacial erratics, roche moutonnées, U-shaped valleys, glacial polish, and striations.

Other Volcanic Features

The volcanic units in Devils Postpile National Monument were originally grouped into a single map unit labeled "Andesite of the Devils Postpile" (fig. 4, Map Unit Properties Table, and Attachment I). However, more recent geologic studies have identified the following individual volcanic units within the Devils Postpile flow: basalt of the Devils Postpile; andesite of Mammoth Pass; rhyodacite of Rainbow Falls; and basalt of the Buttresses (Huber and Eckhardt 2002).

The Mammoth Pass lava, once thought to be the source of the Postpile basalt, erupted from a vent near Mammoth Pass approximately 67,000 years ago (Mahood et al. 2000). Extruded from a higher elevation than the Postpile basalt, the Mammoth Pass lava cascaded into the Middle Fork valley toward the Postpile. But unlike the Postpile basalt, the Mammoth Pass lava is andesite, a rock containing more silica than basalt and lacking the small but visible crystals of feldspar that characterize the Postpile basalt.

Lava erupting from vents just downstream from the Devils Postpile solidified into the rhyodacite of Rainbow Falls. In comparison to andesite, rhyodacite contains more silica and tends to be lighter-colored and finer-grained. Perhaps the most striking difference between the units is the presence of near-horizontal plate-like ("platy") jointing in the rhyodacite, a feature displayed along the road west of Reds Meadow that leads to the Rainbow Falls trailhead.

The basalt lava that formed the Buttresses erupted from vents west of the monument and flowed eastward into the Middle Fork valley. The Buttresses lie southwest of the Postpile and form the oldest volcanic unit formerly considered part of the Devils Postpile (fig. 4). Superficially, the two basalts look alike. However, the abundant visible crystals in the Buttress basalt are composed of pyroxene, while the visible crystals in the Postpile basalt are feldspar. Pyroxenes belong to a group of dark-colored minerals that form short stubby crystals. Feldspars, on the other hand, form light-colored to translucent crystals.

The tuff of Reds Meadow (fig. 4) represents an entirely different type of volcanic rock found near the monument. Similar to the aerially extensive Bishop Tuff that erupted from the Long Valley Caldera about 760,000 years ago, the tuff at Reds Meadow resulted from a fiery ash cloud released during an explosive volcanic eruption. The blistering hot volcanic ejecta fused together to form a "welded" tuff. Exposures of this tuff behind the old ranger cabin east of Reds Meadow form columnar joints, but the columns are nearly horizontal rather than vertical.

The only volcanic event younger than the one that produced the Postpile flow is the one that built the Red Cones, two basalt cinder cones located about 2.4 km (1.5 mi) southeast of Devils Postpile National Monument. The two cones have well-preserved summit craters. A basalt flow that issued from the base of the southern cone extended down Crater Creek to within 1.6 km (1 mi) of the Middle Fork. Because they are less than 10,000 years old, the Red Cones and associated basalt flow escaped the powerful excavating force of glacial erosion. The eroded pile of cinders near Upper Soda Springs Campground may have once looked like the Red Cones (Huber and Eckhardt 2002).

Pumice, a frothy volcanic glass, covers the ground at various places in the monument area. Pumice is so porous and lightweight, it can float in water. The unweathered, loosely compacted pumice formed in post-glacial time when gas-rich magma of high silica content erupted from the Mono and Inyo Craters northeast of Devils Postpile National Monument.

Rainbow Falls

Plummeting 31 m (101 ft) over a cliff of volcanic rock, Rainbow Falls presents a striking contrast of whitewater against black, volcanic cliffs (fig. 12). Located near the southern end of the monument about 4 km (2.5 mi) from the Ranger Station, Rainbow Falls is the highest waterfall on the Middle Fork of the San Joaquin River (fig. 1). On sunny summer days, rainbows appear in its mist.

Although glaciers polished the surface of the volcanic rock and widened the river's canyon, they did not create the present falls. Rather, the key to the falls resides in two unequally hard, horizontal rock layers that compose the cliff. The eruption that produced the rhyodacite of Rainbow Falls occurred in two stages. Lava from the first pulse flowed about 1 km (0.6 mi) westward and pooled in the Middle Fork of the San Joaquin drainage. The second pulse of lava covered the first, allowing the initial flow to cool slowly and to fracture into the horizontal, thinly–spaced joints characteristic of the Rainbow Falls rhyodacite (Huber and Eckhardt 2002; http://geomaps.wr.usgs.gov/parks/depo/dpgeol13.html, accessed November 2009). The massive, poorly jointed upper layer is more resistant to erosion than the lower platy layer.

As water cascades over the cliff, the less resistant rock at the base of the falls wears away in a process known as "undercutting." Undercutting erodes the softer rock, creating an alcove, or cavern, beneath the massive layer (fig. 12). As the upper layer loses its support, it eventually caves in and breaks into boulders and rock debris at the bottom of the falls.

The falls are also a product of channel migration. Following the Pleistocene ice age, the Middle Fork flowed about 460 m (1,500 ft) west of its present location (fig. 13). This older channel eroded through the lava flows down to granite, leaving a cliff of volcanic rocks for its eastern bank. For reasons that are still unclear, the Middle Fork's channel diverted to the east at some point upstream from the present falls. The river left its bed to follow this new path until it returned to its old channel by cascading over the cliff it had cut earlier.

Normally, rivers tend to erode channels to a uniform gradient, beveling off and eventually eliminating irregularities such as waterfalls. Because of the two unequally hard, horizontal rock layers, however, Rainbow Falls remains a significant irregularity in the gradual slope of the Middle Fork's channel. Due to constant undercutting, the cliff has retreated up the valley about 152 m (500 ft) from its initial location (Huber and Eckhardt 2002).

Mineral Springs

Mineral springs, both hot and cold, occur within or near the monument and are associated with recent volcanic activity. One cold, highly-carbonated spring flows onto a gravel bar on the west side of the Middle Fork in Soda Springs Meadow, about 0.2 km (0.1 mi) north of the Devils Postpile. The mineral springs and seeps often occur where gasses and water vapor escape from hot areas deep in the Earth and combine with groundwater near the surface. Iron in acidic spring water, oxidized upon exposure to the atmosphere, stains the river gravel orange in the vicinity of Soda Springs (fig. 14). Just east of the monument, a hot spring at Reds Meadow further attests to the continuing volcanic activity in the area.

San Joaquin River and Soda Springs Meadow

The Middle Fork of the San Joaquin River meanders through Soda Springs Meadow (fig. 15). Unlike its ancestral counterpart whose channel eroded vertically through lava flows, the Middle Fork's channel erodes laterally, from side-to-side across its floodplain. Typical of meandering streams, the main current (channel at maximum depth) migrates from the outside loop of one bend to the outside bank of the next bend. Point bars develop along the inside bend as the river's energy decreases and sediment is deposited. Opposite the point bar, a steep cutbank forms where the main current cuts into unconsolidated sediment and soil. Riffles form where shallow water flows swiftly over coarser sediment often located in the straight section of the stream between meander loops. Crescent-shaped patterns in the meadow, composed of unconsolidated sand and silt, mark abandoned river bends (meander scars). The lush riparian corridor provides a healthy vibrant habitat for plants and animals.

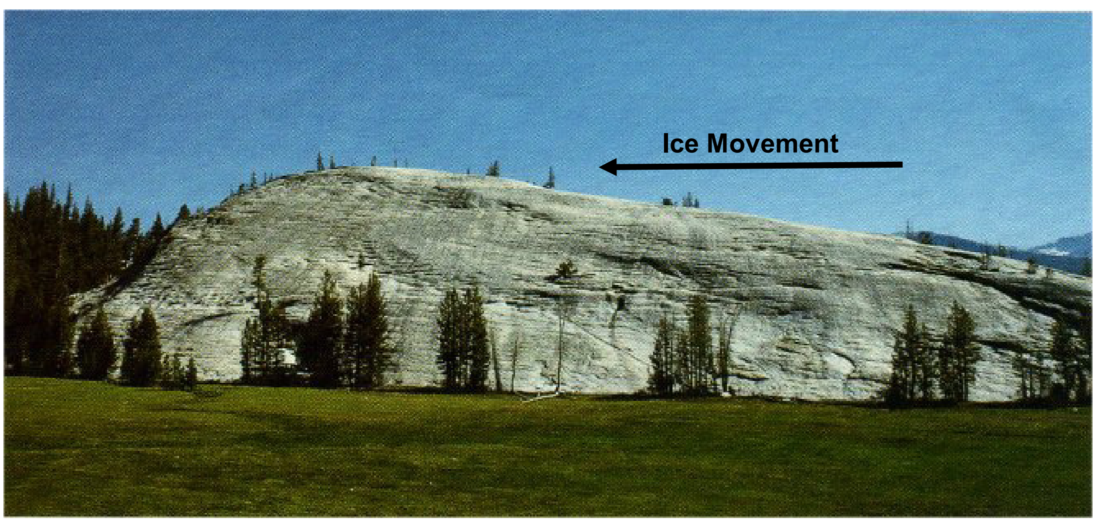


Figure 11. Pothole Dome, a large roche moutonnée in Yosemite National Park. Glaciers shaped Pothole Dome; ice moved from right to left over the bedrock surface (arrow). Plucking occurred on the downstream side; grinding and polishing occurred on the upstream side. U.S. Geological Survey photograph from Huber (1987), available at: http://pubs.er.usgs.gov/usgspubs/b/b1595. Accessed November 2009.

Figure 12. Rainbow Falls, Middle Fork of the San Joaquin River, Devils Postpile National Monument. The water tumbles 31 m (101 ft) over a cliff composed of rhyodacite. Undercutting has eroded an alcove to the left of the waterfall. Photograph courtesy Vincent Santucci (NPS George Washington Memorial Parkway).

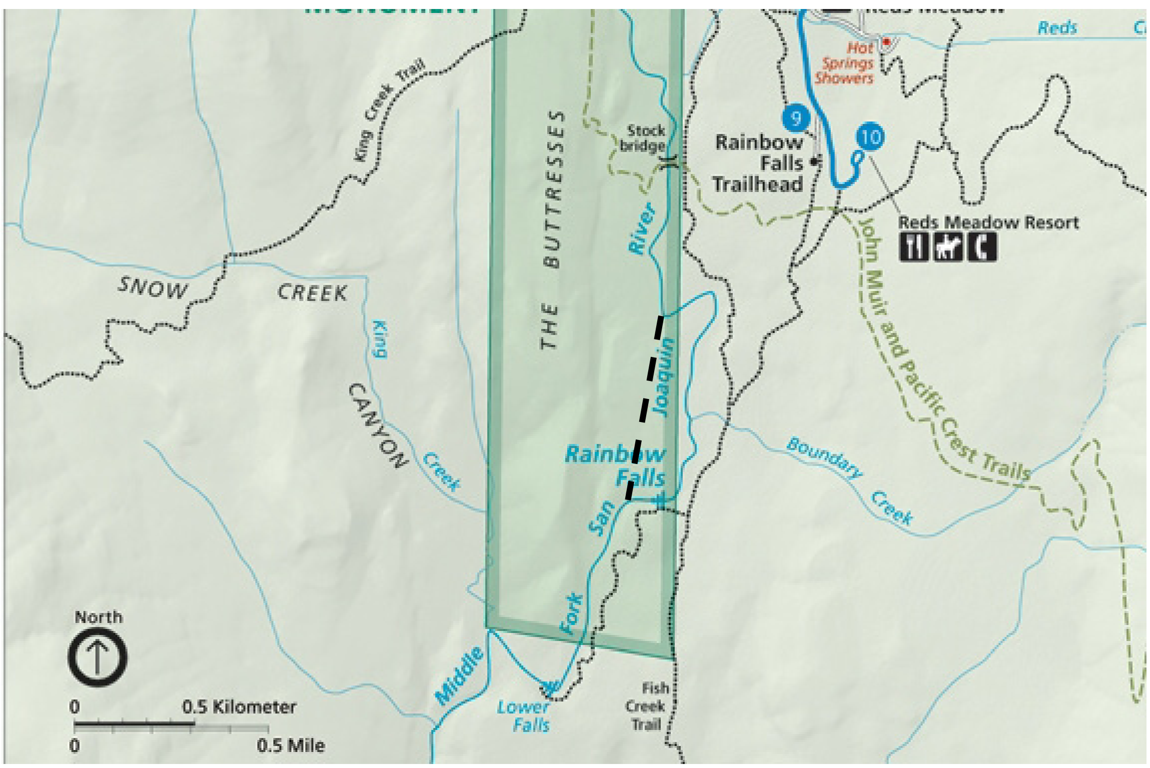


Figure 13. Original channel of the Middle Fork of the San Joaquin River, Devils Postpile National Monument. The dashed, black line depicts the original channel that eroded vertically through solidified lava flows. When the Middle Fork flowed back to its original channel from the east, it flowed over the previously eroded cliff of rhyodacite, forming Rainbow Falls. Modified from National Park Service map.

Figure 14. Iron from Soda Springs creates the orange color visible in mid to late summer in Devils Postpile National Monument. National Park Service photograph, available at: http://www.nps.gov/depo/photosmultimedia/photogallery.htm. Accessed November 2009.

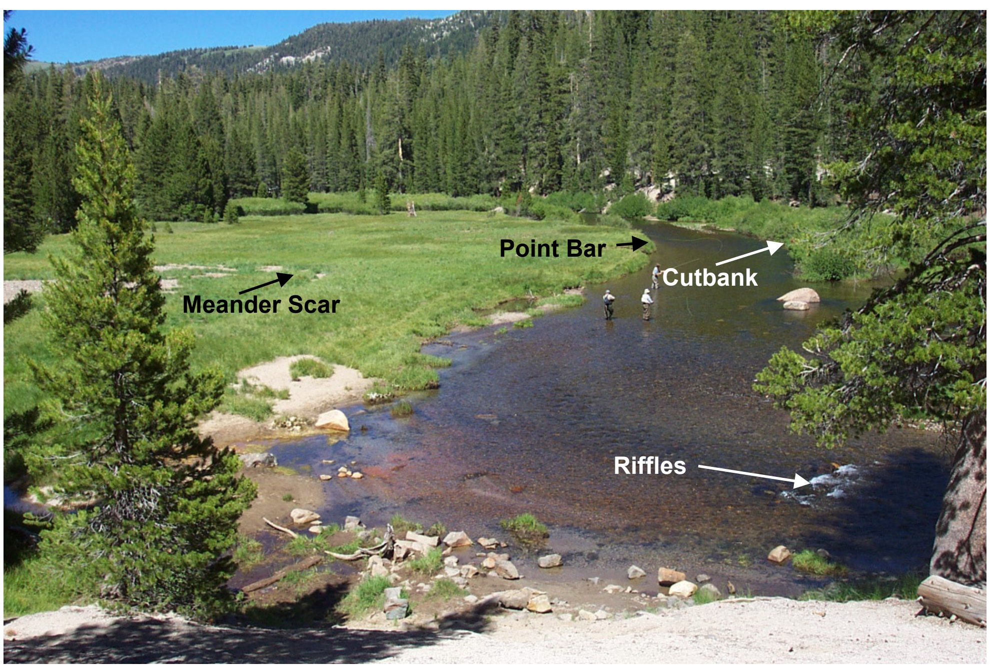


Figure 15. The Middle Fork of the San Joaquin River meanders through Soda Springs Meadow, creating geomorphic features such as point bars, cut banks, and in-stream riffles. A meander scar defines the pattern of a previous channel. Modified from a National Park Service photograph, available at: http://www.nps.gov/depo/photosmultimedia/photogallery.htm. Accessed November 2009.

Map Unit Properties

This section identifies characteristics of map units that appear on the Geologic Resources Inventory digital geologic map of Devils Postpile National Monument. The accompanying table is highly generalized and is provided for background purposes only. Ground-disturbing activities should not be permitted or denied on the basis of information in this table.

Geologic maps facilitate an understanding of Earth, its processes, and the geologic history responsible for its formation. Hence, the geologic map for Devils Postpile National Monument provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report. Geologic maps are two-dimensional representations of complex three-dimensional relationships; their color coding illustrates the distribution of rocks and unconsolidated deposits. Bold lines that cross or separate the color patterns mark structures such as faults and folds. Point symbols indicate features such as dipping strata, sample localities, mines, wells, and cave openings.

Incorporation of geologic data into a Geographic Information System (GIS) increases the usefulness of geologic maps by revealing the spatial relationships among geologic features, other natural resources, and anthropogenic features. Geologic maps are indicators of water resources because they show which rock units are potential aquifers and are useful for finding seeps and springs. Geologic maps are not soil maps, and do not show soil types, but they do show parent material—a key factor in soil formation. Furthermore, resource managers have used geologic maps to make connections between geology and biology; for instance, geologic maps have served as tools for locating sensitive, threatened, and endangered plant species, which may prefer a particular rock unit.

Although geologic maps do not show where earthquakes will occur, the presence of a fault indicates past movement and possible future seismic activity. Similarly, map units show areas that have been susceptible to hazards such as landslides, rockfalls, and volcanic eruptions. Geologic maps do not show archaeological or cultural resources, but past peoples may have inhabited or been influenced by depicted geomorphic features. For example, alluvial terraces may have been preferred use areas and formerly inhabited alcoves may occur at the contact between two rock units.

The geologic units listed in the following table correspond to the accompanying digital geologic data. Map units are listed in the table from youngest to oldest. Please refer to the geologic timescale (fig. 16) for the age associated with each time period. The table highlights characteristics of map units such as: susceptibility to erosion and hazards; the occurrence of paleontological resources (fossils), cultural resources, mineral resources, and caves or karst; and suitability as habitat or for recreational use. Some information on the table are conjectural and meant to serve as suggestions for further investigation.

The GRI digital geologic maps reproduce essential elements of the source maps including the unit descriptions, legend, map notes, graphics, and report. The following reference is source data for the GRI digital geologic data for Devils Postpile National Monument:

Huber, N.K., and C.D. Rinehart. 1965. *Geologic map of the Devils Postpile quadrangle, Sierra Nevada, California*. Scale 1:62,500. Geologic Quadrangle GQ-437. Reston, VA: U.S. Geological Survey.

The GRI team implements a geology-GIS data model that standardizes map deliverables. This data model dictates GIS data structure including data layer architecture, feature attribution, and data relationships within ESRI ArcGIS software, increasing the overall quality and utility of the data.

GRI digital geologic map products include data in ESRI personal geodatabase, shapefile, and coverage GIS formats, layer files with feature symbology, Federal Geographic Data Committee (FGDC)-compliant metadata, a Windows help file that contains all of the ancillary map information and graphics, and an ESRI ArcMap map document file that easily displays the map. GRI digital geologic data are included on the attached CD and are available through the NPS Data Store (http://science.nature.nps.gov/nrdata/, accessed November 2009).

Geologic History

This section describes the rocks and unconsolidated deposits that appear on the digital geologic map of Devils Postpile National Monument, the environment in which those units were deposited, and the timing of geologic events that created the present landscape.

Using radiometric dates, relative dating techniques, and geological observations from California, Oregon, and Nevada, geologists have pieced together the complex geologic history of the Sierra Nevada region and the western margin of North America (fig. 16). Some of the geologic history can be interpreted in considerable detail, whereas other sections of the geologic record are less complete because data are not available.

For roughly 500 million years, the western margin of North America has been an active tectonic margin that has experienced a broad spectrum of deformation. Sedimentary rock units have been folded and faulted and displaced from their original site of deposition (fig. 17). Magma bodies have cooled at great depths or erupted violently at the surface. These igneous intrusions (batholiths, pluton, and stocks) and extrusive, volcanic rocks are now exposed along the crest of the Sierra Nevada. Episodes of tectonic compression dislodged and transported enormous masses of rock from west to east. In contrast, east-west extensional forces have pulled the region apart. Vast tracks of California coast have wrenched free from the rest of the continent and continue to slide northward. The world renowned columnar basalt columns in Devils Postpile National Monument record a significant, but relatively young, chapter in this remarkable and exceptionally dynamic geologic history.

Paleozoic Era (542 to 251 million years ago)

Latest Proterozoic (2,500 to 542 million years ago) and Cambrian (542 to 488.3 million years ago) rocks in the western United States comprise three vertically stacked stratigraphic units: 1) a Late Proterozoic diamictite (poorly sorted sedimentary rock) and volcanic succession; 2) a latest Proterozoic and Lower Cambrian succession of terrigenous detritus; and 3) an uppermost Lower Cambrian through Upper Cambrian marine carbonate and shale sequence (Stewart 1991). Approximately 500 million years ago, most of what is now California lay submerged to the west of the emerging North American continent (fig. 18). The western margin of North America was a passive margin—like today's East Coast—with the continent and its adjacent ocean basin traveling on the same lithospheric plate.

Interpretation of the Cambrian through Silurian geologic history of the Sierra Nevada presents a challenge because subsequent mountain-building episodes, emplacement of Sierra Nevada batholiths, and other tectonic events have deformed and displaced these Early Paleozoic rock units. From the Late Devonian (385.3 to 359.2 million years ago) through the Early Mississippian (359.2 to 345.3 million years ago), the passive western margin along the California coast transformed into an active subduction zone with oceanic crust being subducted beneath the North American plate in the initial phase of the Antler Orogeny (fig. 16) (Dickinson 1977; Poole and Sandberg 1977; Johnson et al. 1991). This oceanic-continental crust collision generated the Roberts Mountains Thrust, a thrust fault that displaced Cambrian through Devonian strata from west to east. Mountains emerged in central Nevada, and marine waters spread over a large portion of the continent (fig. 19).

The Roberts Mountains Thrust and subsequent Paleozoic tectonic episodes are known as orogenic "continent-accretion phases" wherein rocks were added to the western margin of the craton. Mississippian through Permian strata in the southwestern United States document a series of tectonic episodes that were both local and regional in scale and included uplift, tilting, folding, erosion, basin segmentation, and subsidence (Trexler et al. 1991).

During the Pennsylvanian, thrust faults associated with oceanic-continental convergence along the western margin accreted oceanic deposits to the mainland. These marine sediments were dominated by dark chert, deep-marine mud, igneous rocks, dark shale, siltstone, isolated carbonate plateaus and atolls, and locally thick basinal and slope-margin clastic sediments (Ross 1991). South America began closing with North America, and the forces of this continent-continent collision were felt far inland, generating the northwest-southeast trending Ancestral Rocky Mountains.

Several basins that would eventually become prolific oil- and gas- producing basins formed in the late Paleozoic including the Delaware, Midland, and Paradox basins (fig. 20). The Sonoma Orogeny, a Late Permian-Triassic tectonic episode, further accreted marine sediments onto the continental margin as the major land masses continued to suture together to form the supercontinent, Pangaea (Trexler et al. 1991; Dubiel 1994; Dunston et al. 2001).

Mesozoic Era (251 to 65.5 million years ago)

Triassic-Jurassic Periods (251 to 145.5 million years ago)

Extension (plates pulling apart) and strike-slip (plates sliding past each other) faulting of the crust during the Early Triassic truncated the continental margin of California and formed a north-trending continental margin that paralleled the foothills of the current Sierra

Nevada. This north-trending margin became the locus of eastward subduction beneath North America in the Late Triassic (Schweickert 1978; Oldow et al. 1989; Saleeby et al. 1992; Stevens 1991).

The Late Permian—Early Triassic Sonoma Orogeny compressed, shortened, and deformed the sequence of rocks now exposed in the Ritter Range, west and north of Devils Postpile National Monument (Schweickert 1978; Oldow et al. 1989). Accreted Paleozoic and Mesozoic sedimentary and volcanic rocks in the Ritter Range record evidence of long vanished seaways and island volcanoes that existed west of the present-day Sierra Nevada. An 11 km (7 mi) thick sequence of ash-flow tuffs, lava flows, bedded pyroclastic rocks, and marine limestones document latest Permian to mid-Jurassic deposition across a low-lying terrain periodically inundated by rising sea level (Fiske and Tobisch 1978).

Plate subduction along the active western margin of North America continued throughout the Mesozoic. As the oceanic plate subducted beneath the overriding North American continent, magma was generated at depth and belts of volcanoes formed atop the overriding plate, parallel to the subduction zone in a manner similar to today's Mount St. Helens and other volcanoes in the Cascade Range (fig. 21A).

Significant magma was generated beneath the Cordillera in the Middle Jurassic, and volcanic islands formed an unknown distance west or southwest of the west coast of North America (Huber and Rinehart 1965; Hamilton 1978; Schweickert 1978; Oldow et al. 1989). During the Late Jurassic, these Middle Jurassic volcanic islands accreted to the North American continent.

Major tectonic plate reorganization occurred during the Late Jurassic. The Gulf of Mexico opened and the North American lithospheric plate rotated counterclockwise. To accommodate this plate motion, a large transform fault zone (or "megashear"), referred to as the Mojave-Sonora megashear, developed at a fairly high angle to the west coast (relatively parallel to what is now the Mexico-United States border) and truncated the southwestern margin of North America. This northwest-southeast trending megashear zone resulted in approximately 800 to 1,000 km (500 to 600 mi) of left-lateral, strike-slip displacement (Kluth 1983; Stevens et al. 2005; Anderson and Silver 2005; Haenggi and Muehlberger 2005).

Cretaceous Period (145.5 to 65.5 million years ago)

Continued subduction along the west coast of North America initiated the Sevier Orogeny about 105 million years ago in the latest Jurassic. The orogeny continued through the Cretaceous and into the Paleogene (fig. 16). The north-south trending Sevier fold-and-thrust belt extends from Canada through western Montana, eastern Idaho, southwestern Wyoming, central Utah, and into southeastern Nevada (Lageson and Schmitt 1994). During the Early Cretaceous, the orogeny transported regional-scale Proterozoic and Paleozoic megathrust sheets of rock from west to east (DeCelles 2004). Later in the Cretaceous, the orogeny shortened the crust along weak bedding planes in relatively shallow Paleozoic and Mesozoic sedimentary rock, producing "thin-skinned" thrust faults that generally get younger to the east. In contrast, the Late Cretaceous to Eocene Laramide Orogeny produced "basement-cored" reverse faults that often took advantage of preexisting faults that formed during the Late Precambrian (Gries 1983; Erslev 1993; DeCelles 2004).

Sevier thrusting resulted in a greatly thickened crust in the region that would become the Basin- and- Range physiographic province. The thickened crust played an important role in the later pull-apart (tensional) forces that produced the present Sierra Nevada, the Basin- and-Range province, and episodes of Cenozoic volcanism (Livaccari 1991; Kiver and Harris 1999).

Emplacement of continental-margin plutons from Mexico to the Alaskan peninsula and volcanic activity above the associated subduction zone reached maximum development in the Cretaceous (Oldow et al. 1989; Christiansen et al. 1994; Dubiel 1994; Lawton 1994; Peterson 1994). Rocks and sediment caught in the subduction zone were bent, broken, and metamorphosed as they were compressed against and under the North American plate.

As the oceanic plate descended into the asthenosphere and mantle part of the lithosphere, rocks melted and magma was generated that had the composition of basalt or andesite, dark-colored rocks low in silica. The magma rose through the silica-rich continental crust, partially melting the overriding lithosphere, and becoming more granitic. About 140 to 80 million years ago, the granitic magma that would become the Sierra Nevada batholith pooled at depths of only 3 to 8 km (1.8 to 4.9 mi) beneath the active volcanoes at the surface (Fiske and Tobisch 1978; Hamilton 1978; Huber 1987; Oldow et al. 1989; Kiver and Harris 1999).

The Sierra Nevada batholiths (including those now exposed within Yosemite National Park), a composite mass about 100 km (40 mi) wide, consists of hundreds of distinct plutons that range in area up to 1,000 sq km (380 sq mi) (Hamilton 1978). Volcanic deposits on the crest of the Sierra Nevada and Ritter Range are the extrusive equivalents of their adjacent plutons. Intense volcanic activity produced extraordinary amounts of volcanic material. For example, a 4-km (2.5-mi)- thick section of ash-flow tuff in the Ritter Range contains a lens of caldera-collapse breccia more than 1-km (0.6-mi)- thick, suggesting the sequence records the remains of a mid-Cretaceous caldera fill complex (Fiske and Tobisch 1978).

As Sevier orogenic thrust packages thickened the crust along the western margin of North America, the Western Interior Basin, the region east of the fold-and-thrust belt, subsided. At a time when mountains rose along the western margin, rifting between North and South America opened the Gulf of Mexico, and seawater spread northward into the Western Interior Basin, which would soon become the Western Interior Seaway.

Marine water also began to transgress southward onto the continent from the Arctic region.

The seas advanced and retreated many times during the Cretaceous until the most extensive interior seaway ever recorded drowned much of western North America. The elongate Western Interior Seaway extended from today's Gulf of Mexico to the Arctic Ocean, a distance of about 4,800 km (3,000 mi) (fig. 22).

The Cretaceous seaway was the last marine incursion into the interior of North America. The seaway receded from the continental interior with the onset of the Laramide Orogeny (about 70 to 35 million years ago). This orogeny marked a pronounced eastward shift in tectonic activity as the angle of the subducting slab of oceanic crust flattened and compressive forces were felt throughout northern Arizona and Utah and into Colorado (fig. 21B). Unlike Sevier thrust faults, Laramide thrust faults displaced deeply-buried Precambrian plutonic and metamorphic rocks that are now exposed in the core of the Rocky Mountains. Sevier thrust faults dip at a low angle (generally 10° to 15°) relative to Earth's surface. In contrast, Laramide thrust faults have steeply-dipping fault planes at the surface that curve and flatten in Precambrian crystalline rocks at depths to 9 km (5.7 mi [30,000 ft]) below sea level (Gries 1983; Erslev 1993).

Once the magmatic source for the ancestral Sierra Nevada was eliminated, erosion became the dominant force shaping the range. By the end of the Cretaceous, most of the older volcanic and metamorphic rocks had been eroded, exposing the granite core of the ancestral Sierra (Huber 1987; Huber and Eckhardt 2002). Elevations of the mountain summits were low compared to the present-day Sierra Nevada, and did not inhibit the westward flow of streams and rivers draining the interior of the continent.

Cenozoic Era (65.5 million years ago to the present)

Paleogene and Neogene ("Tertiary") Period (65.5 to 2.6 million years ago)

The Devils Postpile region contains exposures of Tertiary andesite and quartz latite, a light- gray to dark- or purplish- gray volcanic rock with abundant plagioclase and lesser biotite and amphibole phenocrysts; however, no Tertiary exposures are found in the monument (Huber and Rinehart 1965).

Until approximately 70 million years ago, nearly the entire western North American margin was in compression, causing thrusting and margin-parallel transcurrent faulting. In central California, west and south of the Sierra plutonic belt, the proto-San Andreas fault formed in the Late Cretaceous to Paleocene. Oblique subduction of the Farallon plate beneath North America resulted in approximately 1,500 km (930 mi) of northward displacement of the Salinian Terrane, a wedge-shaped crustal block of west-central California, along the proto-San Andreas fault. The Salinian Terrane is bounded by the San Andreas fault on the east, the Pacific Ocean on the west, and is exposed from Point Arena south to Point Sur (Oldow et al. 1989).

Widespread magmatism occurred along the continental margin during the late Oligocene and early Miocene. By the early Miocene (23 to 16 million years ago), the divergent plate boundary (spreading ridge) that separated the Pacific plate from the Farallon plate intersected the western margin of the North American plate (fig. 23). The collision of the divergent boundary with the active margin terminated subduction along this segment of the coast and activated the San Andreas strike-slip fault. As one of California's most outstanding geologic features, the San Andreas fault is more than 1,000 km (620 mi) long, with a cumulative right-lateral displacement of greater than 320 km (200 mi) (Oldow et al. 1989).

The coastal region was segmented into individual basins. Crustal extension and strike-slip faulting (transtension), accompanied by oblique shortening and strike-slip (transpression), generated extensive folding and thrust faulting (Oldow et al. 1989).

The change from subduction to strike-slip movement further removed support for the thick crust in the Great Basin. The crust collapsed under the Great Basin, widening the Basin- and -Range Province. Crustal thinning produced tensional (pull-apart) faults in the eastern Sierra Nevada and Basin-and-Range and the subsequent rise of hot mantle material. The resulting thermal expansion and partial melting of the mantle reduced rock density, and account for the unusually high elevation of the eastern Sierra (Huber 1987; Park et al. 1996).

Considerable debate and research continues with regard to when the Sierra Nevada developed as a mountain range. One view, based on the isotopic composition of authigenic minerals (typically clay minerals that have not been transported from the spot where they formed), suggests that the Sierra Nevada existed as a major topographic feature throughout much of the Cenozoic (Chamberlain and Poage 2000; Chamberlain et al. 2002; Chamberlain et al. 2005; Mulch et al. 2005; Mulch et al. 2006; Cassel et al. 2009). In this view, most of the topography was established in the early Tertiary with little change in elevation occurring over the past 16 million years.

A contrary opinion, based on river incision rates and cosmogenic dating of cave sediments, suggests that a late Cenozoic uplift gave rise to the present elevation of the Sierra Nevada (Stock et al. 2004; Stock et al. 2005). In this view, rapid river incision of approximately 0.2 mm/yr (0.008 in/yr) from 2.7 to 1.5 million years ago supports a tectonically driven, late Pliocene to Quaternary uplift.

Until about 3 million years ago, the main fork of the San Joaquin River may have had its headwaters as far east as Nevada (Huber and Eckhardt 2002). The river crossed what is today the Sierran crest north of Minaret Summit. Highly resistant rocks in the Ritter Range diverted the southwestward flow of the San Joaquin River to the southeast and then south through the Devils Postpile area. South of the Devils Postpile, the river changed its course to the southwest, flowing across the less resistant granite at the south end of the Ritter Range.

About 3 million years ago, lava flows filled the river channel north of Minaret Summit. These lava flows are exposed today as the reddish-colored, layered rocks visible on the slope above the road descending to Agnew Meadows (Huber and Eckhardt 2002). The lava flow and the growth of the east-facing Sierra Nevada escarpment isolated the present San Joaquin drainage basin and blocked any renewal of a trans-Sierra San Joaquin River.

Quaternary Period (2.6 million years ago to present)

Quaternary rocks and sediments unconformably overlie Cretaceous granite and granodiorite in Devils Postpile National Monument (fig. 4). During the Pleistocene Epoch (2.6 million to 11,700 years ago), heavy snowpacks in the Sierra Nevada fed glaciers that descended through stream-cut canyons, deepening and widening them. Ice accumulated on the east slope of the Ritter Range, forming glaciers that flowed down the Middle Fork of the San Joaquin River, shaping today's U-shaped valley. Fractures in the rock helped the glaciers erode and shape the bedrock. The glaciers carved cirques and sculpted the jagged peaks in the neighboring Ritter Range and Minarets.

Volcanic activity coincided with Sierran alpine glaciation. Deposition of the tuff near Reds Meadow occurred concurrent with the volcanic activity that created the Long Valley Caldera about 760,000 years ago. River erosion removed much of the tuff from the central part of the valley and exposed the basalt at the Buttresses. The rhyodacite lava of Rainbow Falls erupted from vents downstream from the present site of the Devils Postpile. About 67,000 years ago, andesite lava erupted near Mammoth Pass and flowed into the Middle Fork valley.

The basaltic lava responsible for the Devils Postpile erupted less than 100,000 years ago, forming a lake of lava that covered several square kilometers of the valley floor. Stream and glacial erosion removed much of the accumulated volcanic rock from the Middle Fork valley and exposed a vertical section of the Devils Postpile. The last glaciation, which ended approximately 12,000 years ago, polished the tops of the famous columns and marked the rocks with glacial striations and grooves.

Less than 10,000 years ago, after the last glacier melted from the valley, the Red Cones and their associated lava flow formed. Airfall pumice deposits along the trails and hillsides fell on the area during the past few hundred years, likely from an eruption from one of the plug domes located along the Mono Craters fissure just east of the Sierra Nevada.

The Mono Craters and Inyo domes between Mono Lake and Mammoth Lakes have been erupting episodically during the past few thousand years. The most recent domes were formed about 600 years ago. The results of glacial activity and recent erosion processes are visible in the dramatic landscape of Yosemite National Park. *The Geologic Story of Yosemite National Park* (Huber 1987) contains a detailed description of the effect of these erosion processes on the landscape at Yosemite, and on the Sierra Nevada in general.

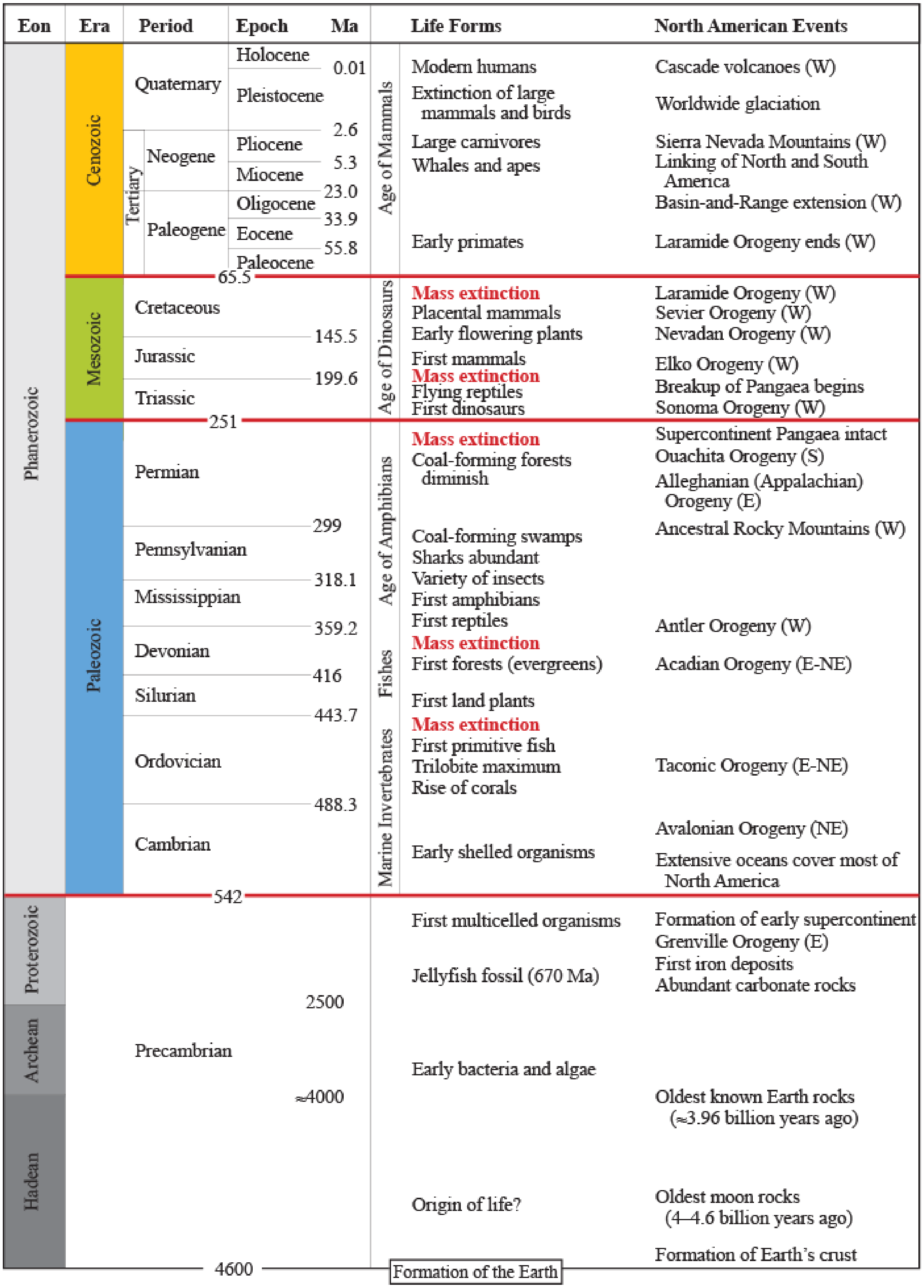
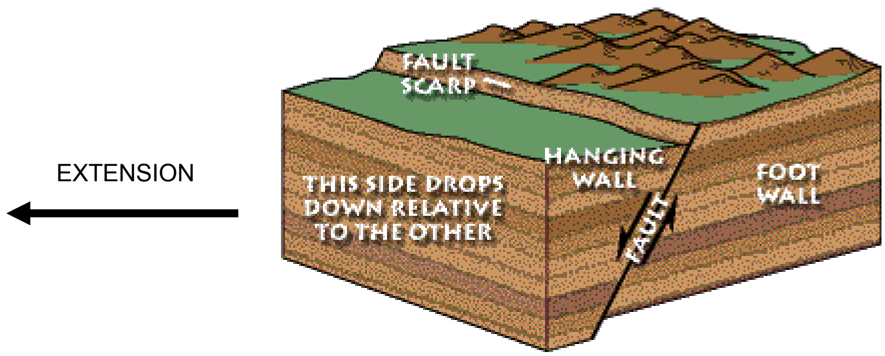
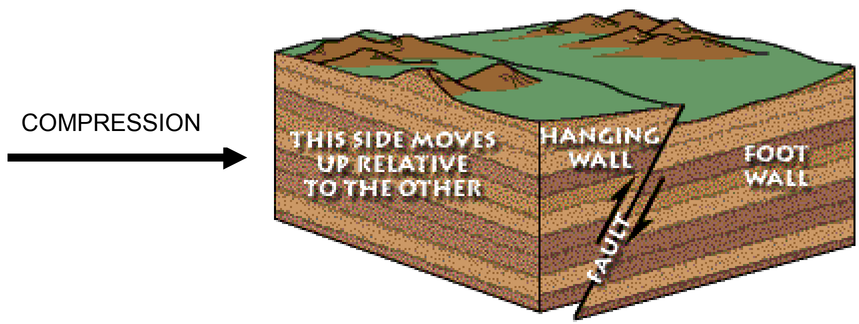


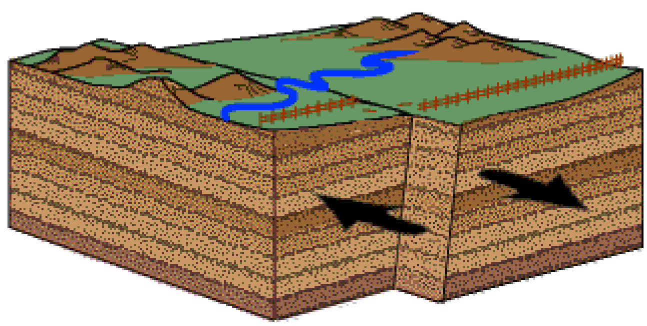
Figure 16. Geologic time scale. Included are major life history and tectonic events occurring on the North American continent. Red lines indicate major unconformities between eras. Radiometric ages shown are in millions of years (Ma). Compass directions in parentheses indicate the regional location of individual geologic events. Adapted from the U.S. Geological Survey, http://pubs.usgs.gov/fs/2007/3015/ with additional information from the International Commission on Stratigraphy. http://www.stratigraphy.org/view.php?id=25. Accessed November 2009.



A) Normal Fault



B) Reverse (thrust) Fault



C) Strike-slip Fault

Figure 17. Diagrams of general fault types. A) In a "normal" fault (top diagram), rocks in the "hanging wall" above the fault plane move downward relative to rocks in the "footwall" below the fault plane. These terms developed as a result of early mining geology. Walking down a fault plane in a mine, miners walked on the "foot" wall, while the rocks that hung above their heads were in the "hanging" wall. Extensional forces commonly generate normal faults. B) In a "reverse" fault (middle diagram), the hanging wall has moved up relative to the footwall. The only difference between a "reverse" fault and a "thrust" fault lies in the angle of the fault plane from the surface of the Earth. If the angle is more than about 15%, the fault is a "reverse" fault. In reverse or thrust faults, compressive forces juxtapose older (underlying), hanging wall strata against younger, footwall strata. Typically, compressive forces fold the strata prior to breaking along the fault plane. C) In "strike-slip" faulting, the rocks on each side of the fault slide laterally past each other. In this case, the slip is "right-lateral" because features (e.g., the fence) on one side of the fault have moved to the right relative to the other side of the fault (as viewed across the fault). Strike-slip faulting usually contains elements of normal faulting and reverse faulting, as well. U.S. Geological Survey graphics, available at: http://geomaps.wr.usgs.gov/parks/deform/gfaults.html. Accessed November 2009.

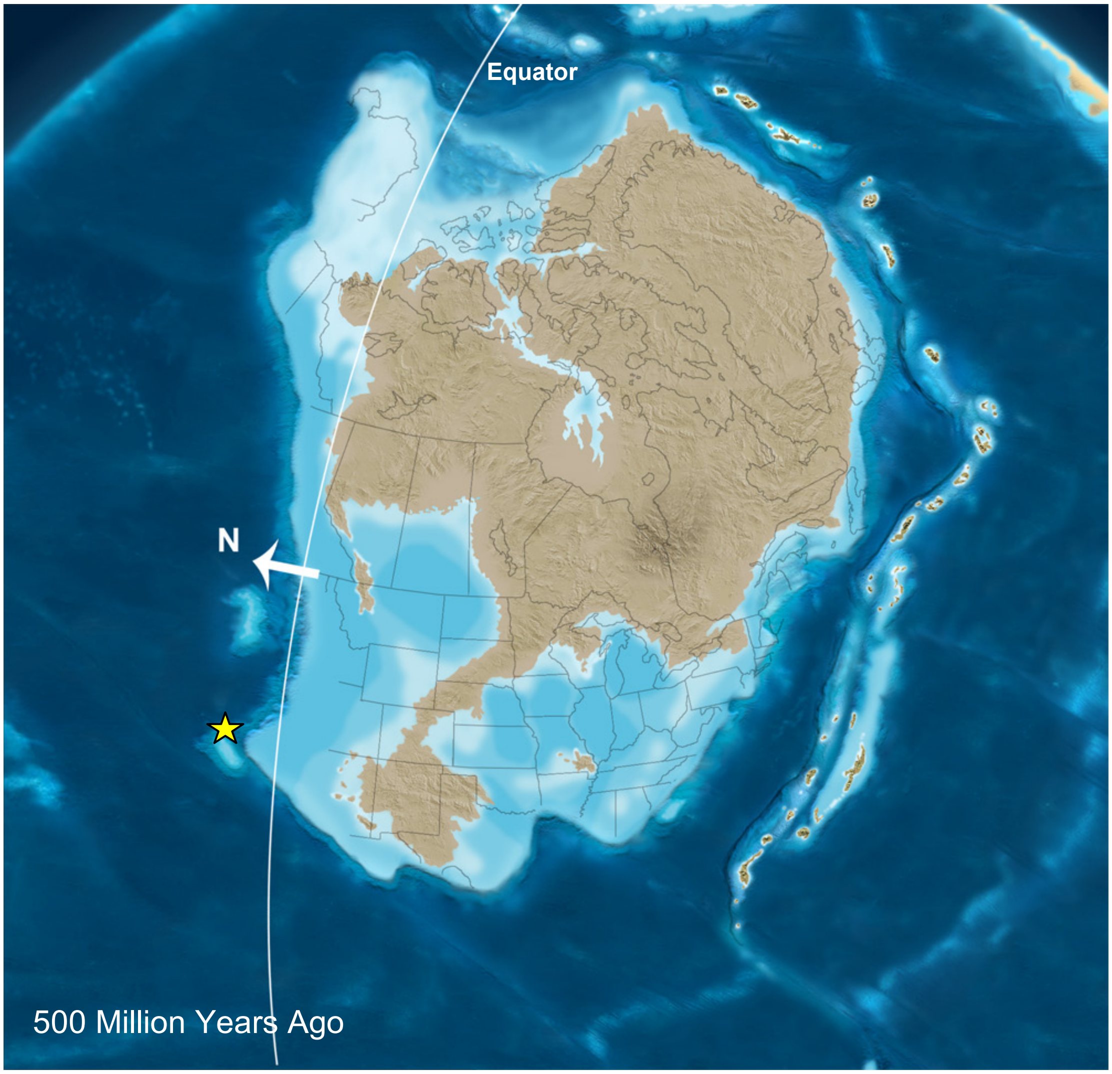


Figure 18. Late Cambrian paleogeographic map of North America. Approximately 500 million years ago, the Sierra Nevada region and future site of Devils Postpile National Monument (yellow star) lay offshore of the "passive" western margin of the emerging North America continent. The brown color indicates exposed land, light blue represents shallow marine, and dark blue shows deep marine. Map modified from the Late Cambrian map of Dr. Ron Blakey (Northern Arizona University), available online at: http://jan.ucc.nau.edu/rcb7/namC500.jpg. Accessed November 2009.

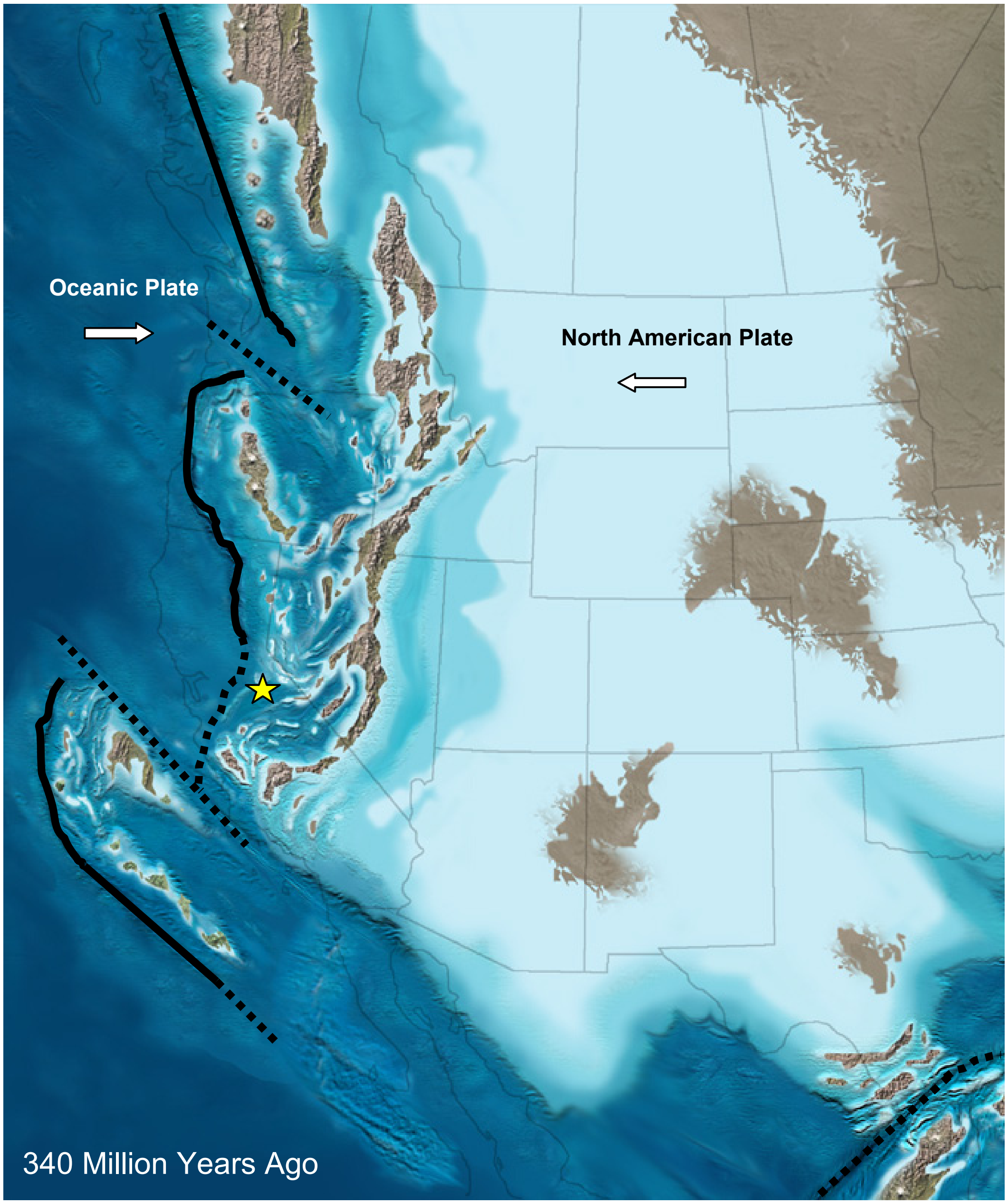


Figure 19. Early Mississippian paleogeographic map of southwestern North America. Approximately 340 million years ago, the western margin of North America was an "active" tectonic margin with a slab of oceanic lithosphere being subducted beneath the North American continent. The Antler Orogeny (mountain-building episode) caused mountains to emerge in central Nevada and Idaho and a major transgression to spread marine environments across western North America. The black line (dashed where uncertain) represents the general location of subduction zones and active margins that bordered western and southeastern North America in the Devonian and Mississippian. The yellow star represents the approximate location of today's Devils Postpile National Monument. The brown color denotes land, light blue represents shallow marine, and dark blue represents deeper marine environments. The general direction of movement of both plates is indicated by the white arrows. Modified from Dr. Ron Blakey (Northern Arizona University), available online at: http://jan.ucc.nau.edu/rcb7/garm340.jpg. Accessed November 2009.

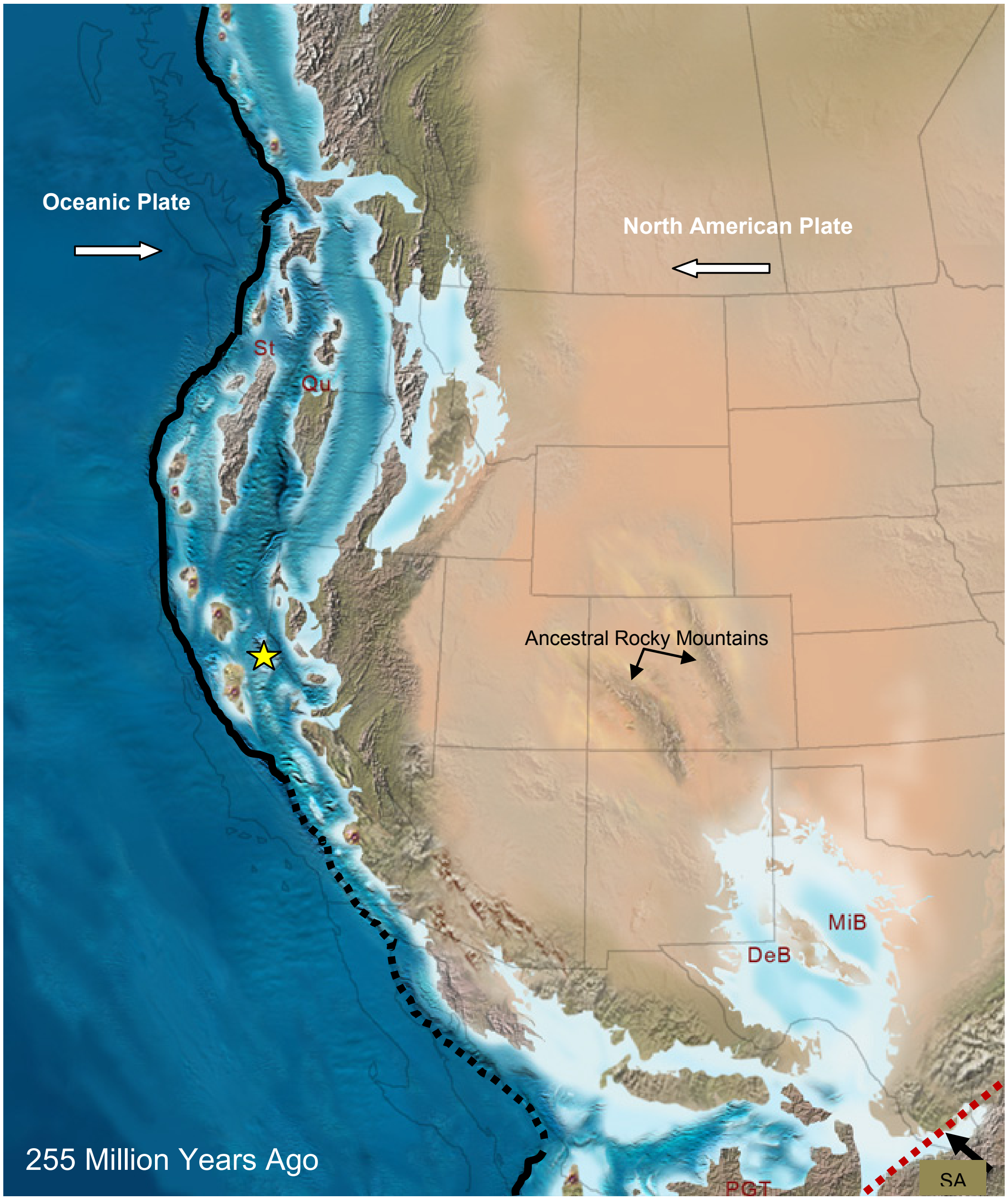
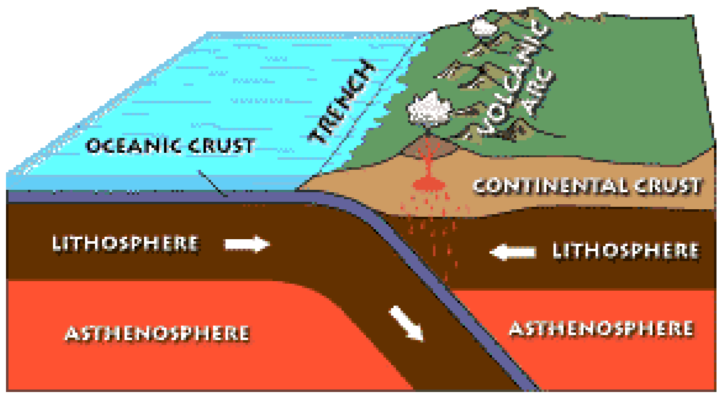
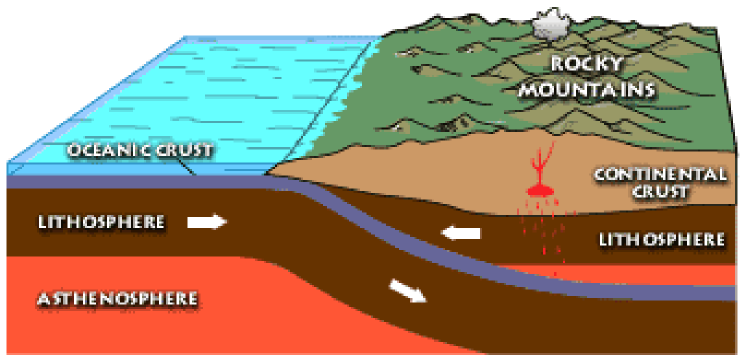


Figure 20. Late Permian paleogeographic map of southwestern North America. About 255 million years ago, the Sonoma Orogeny accreted marine sediments to the western margin of North America. South America (SA) continued to close the proto-Gulf of Mexico and collide with North America. Forces associated with this collision formed the northwest-southeast trending Ancestral Rocky Mountains. By the Late Permian, many of the basins that began forming in the Late Mississippian and Pennsylvanian had filled with sediment, but the Delaware Basin (DeB) and Midland Basin (MiB), prolific oil- and gas- producing basins, continued to subside. By the Triassic, all of the major landmasses had come together to form the supercontinent, Pangaea. The yellow star represents the approximate location of today's Devils Postpile National Monument. The black line marks the general trend of the subduction zone between the North American lithospheric plate and the oceanic plate. The dashed red line represents a very approximate location between South America and North America. The brown and yellowish-brown colors denote land, light blue represents shallow marine, and dark blue represents deeper marine environments. Modified from Dr. Ron Blakey (Northern Arizona University), available online at: http://jan.ucc.nau.edu/rcb7/garm255.jpg. Accessed November 2009.



A) Oceanic-continental convergence (Andean-style, or Cascadian-style, subduction).



B) “Flat slab”-style subduction that gave rise to the Laramide Orogeny and the Rocky Mountains.

Figure 21. Schematic drawings of subduction zones off the western margin of the United States during the Mesozoic. A) In the Early Triassic, the angle of subduction was relatively steep as the oceanic plate converged with the North American continent. This type of subduction is seen today along the western margin of North and South America. B) In the Cretaceous, the subduction zone flattened out in a style known as “flat slab” subduction. Compressive forces and melting were felt much farther inland than normal, giving rise to the Rocky Mountains. Schematics are from the U.S. Geological Survey, available online at: http://geomaps.wr.usgs.gov/parks/province/rockymtn.html. Accessed November 2009.

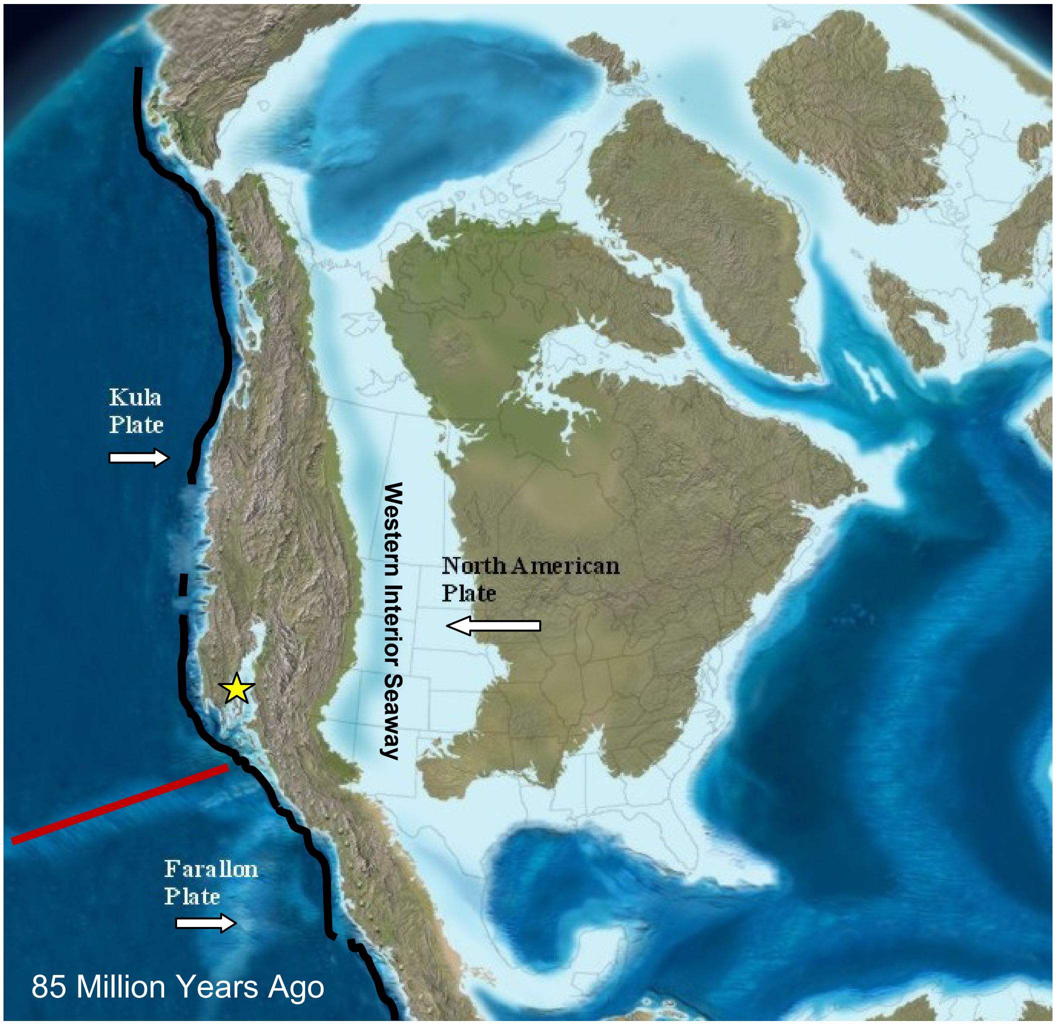


Figure 22. Late Cretaceous paleogeographic map of North America. About 85 million years ago, the Sevier Orogeny, caused by subduction of the Kula and Farallon plates beneath the North American plate, deformed the western margin into a linear chain of mountains. The Western Interior Seaway (WIS) connected the Arctic Ocean with the widening Gulf of Mexico. The yellow star represents the approximate location of today's Devils Postpile National Monument. The thick black line marks the approximate location of the subduction zone. The red line is the approximate location of the spreading center separating the Farallon and Kula plates. The brown color denotes land, light blue represents shallow marine, and dark blue represents deeper marine environments. Modified from Dr. Ron Blakey's (Northern Arizona University) paleogeographic map, available online at: http://jan.ucc.nau.edu/rcb7/namK85.jpg. Accessed November 2009.

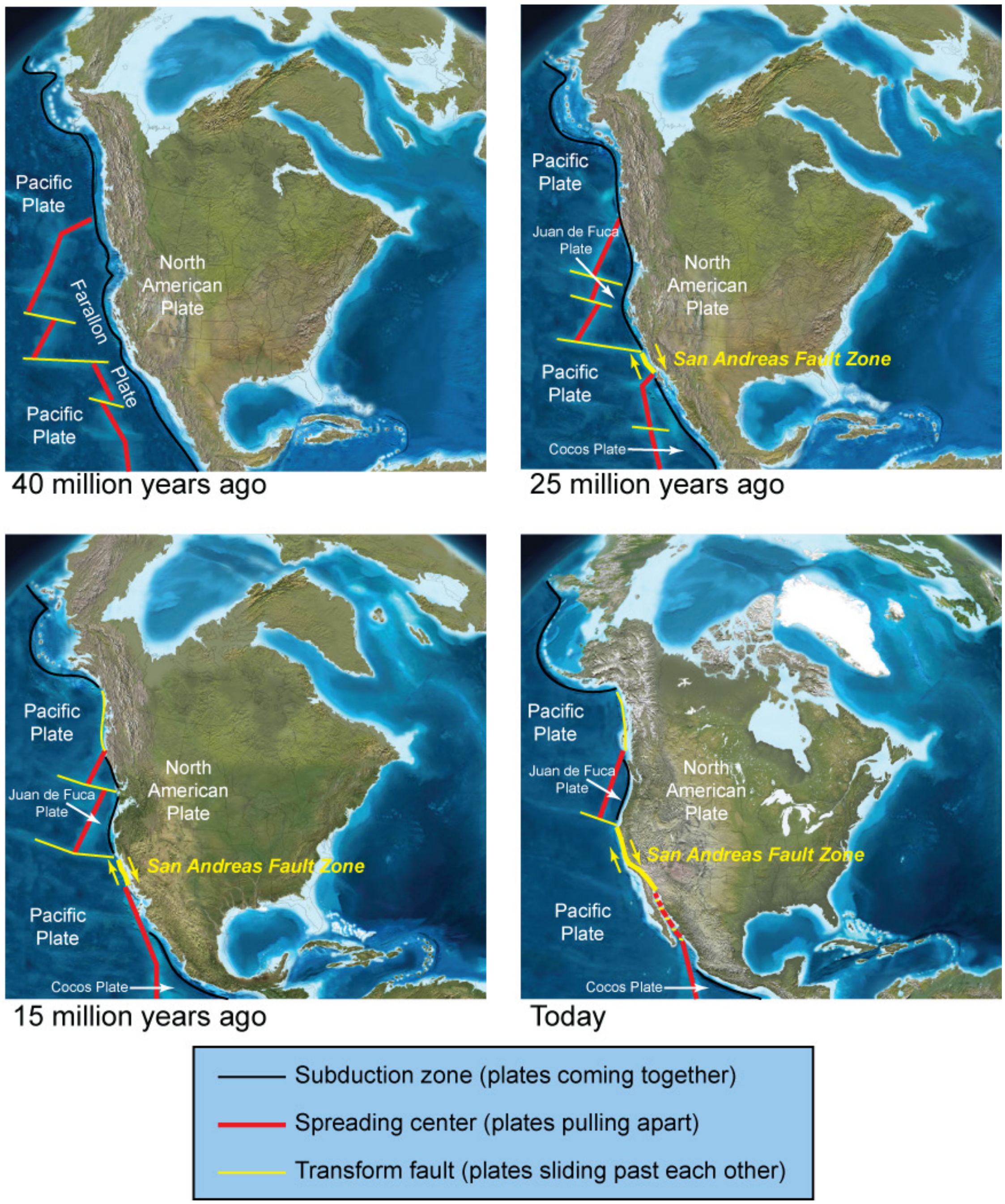


Figure 23. Growth of the San Andreas Fault System. When the spreading center between the Pacific plate and Farallon plate intersected the North American plate, a transform fault formed (San Andreas Fault zone), causing strike-slip (transpressional) movement. The Farallon plate has been subdivided into the Juan de Fuca plate, to the north, and the Cocos plate, to the south. Modified by Jason Kenworthy (NPS Geologic Resources Division) from Dr. Ron Blakey's (Northern Arizona University) paleogeographic maps: http://jan.ucc.nau.edu/~rcb7/nam.html, accessed January 2010.

Glossary

This glossary contains brief definitions of technical geologic terms used in this report. Not all geologic terms used are referenced. For more detailed definitions or to find terms not listed here please visit: http://geomaps.wr.usgs.gov/parks/misc/glossarya.html. Definitions are based on those in the American Geological Institute Glossary of Geology (fifth edition; 2005).

absolute age. The geologic age of a fossil, rock, feature, or event in years; commonly refers to radiometrically determined ages.

active margin. A tectonically active margin where lithospheric plates come together (convergent boundary), pull apart (divergent boundary) or slide past one another (transform boundary). Typically associated with earthquakes and, in the case of convergent and divergent boundaries, volcanism. Compare to "passive margin."

alluvium. Stream-deposited sediment.

alpine glacier. A glacier occurring in a mountainous region; also called a valley glacier.

amygdule. A gas cavity or vesicle in an igneous rock, which is filled with secondary minerals.

andesite. Volcanic rock commonly associated with subduction zone volcanoes. Named for the subduction zone volcanoes of the Andes Mountains.

aphanitic. Describes the texture of fine-grained igneous rocks where the different components are not distinguishable with the unaided eye.

ash (volcanic). Fine pyroclastic material ejected from a volcano (also see "tuff").

authigenic. Describes rocks or minerals that have not been transported from where they formed.

basalt. A dark-colored, often low-viscosity, extrusive igneous rock.

basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie rocks exposed at the surface.

basin (sedimentary). Any depression, from continental to local scales, into which sediments are deposited.

basin (structural). A doubly-plunging syncline in which rocks dip inward from all sides (also see dome).

batholith. A massive, discordant pluton, larger than 100 km^2 (40 mi^2), and often formed from multiple intrusions of magma.

bed. The smallest sedimentary strata unit, commonly ranging in thickness from one centimeter to a meter or two and distinguishable from beds above and below.

bedding. Depositional layering or stratification of sediments.

block (fault). A crustal unit bounded by faults, either completely or in part.

breccia. A coarse-grained, generally unsorted sedimentary rock consisting of cemented angular clasts greater than 2 mm (0.08 in).

calcareous. Describes rock or sediment that contains the mineral calcium carbonate ($CaCO_3$).

calcic. Describes minerals and igneous rocks containing a relatively high proportion of calcium.

caldera. A large bowl- or cone-shaped depression at the summit of a volcano. Formed by explosion or collapse.

carbonaceous. Describes a rock or sediment with considerable carbon content, especially organics, hydrocarbons, or coal.

cementation. Chemical precipitation of material into pores between grains that bind the grains into rock.

chemical sediment. A sediment precipitated directly from solution (also called nonclastic).

cirque. A deep, steep-walled, half-bowl-like recess or hollow located high on the side of a mountain and commonly at the head of a glacial valley. Produced by the erosive activity of a mountain glacier.

clastic. Describes rock or sediment made of fragments of pre-existing rocks (clasts).

clay. Can be used to refer to clay minerals or as a sedimentary fragment size classification (less than 1/256 mm [0.00015 in]).

clinopyroxene. A group name for pyroxene minerals crystallizing in the monoclinic system.

conglomerate. A coarse-grained, generally unsorted, sedimentary rock consisting of cemented, rounded clasts larger than 2 mm (0.08 in).

continental crust. Crustal rocks rich in silica and alumina that underlie the continents; ranging in thickness from 35 km (22 mi) to 60 km (37 mi) under mountain ranges.

continental shield. A continental block of Earth's crust that has remained relatively stable over a long period of time and has undergone minor warping compared to the intense deformation of bordering crust.

convergent boundary. A plate boundary where two tectonic plates are colliding.

cordillera. A Spanish term for an extensive mountain range; used in North America to refer to all of the western mountain ranges of the continent.

country rock. The rock surrounding an igneous intrusion or pluton. Also, the rock enclosing or traversed by a mineral deposit.

craton. The relatively old and geologically stable interior of a continent (also see "continental shield").

crust. Earth's outermost compositional shell, 10 to 40 km (6 to 25 mi) thick, consisting predominantly of relatively low-density silicate minerals (also see "oceanic crust" and "continental crust").

cryptocrystalline. Describes a rock texture where individual crystals are too small to be recognized and separately distinguished with an ordinary microscope.

crystalline. Describes a regular, orderly, repeating geometric structural arrangement of atoms.

dacite. A fine-grained extrusive igneous rock similar to andesite but with less calcium-plagioclase minerals and more quartz.

deformation. A general term for the process of faulting, folding, and shearing of rocks as a result of various Earth forces such as compression (pushing together) and extension (pulling apart).

dextral fault. See "strike-slip fault."

diamictite. Poorly sorted, noncalcareous, sedimentary rock with a wide range of particle sizes.

dike. A narrow igneous intrusion that cuts across bedding planes or other geologic structures.

dip. The angle between a bed or other geologic surface and horizontal.

dip-slip fault. A fault with measurable offset where the relative movement is parallel to the dip of the fault.

divergent boundary. An active boundary where tectonic plates are moving apart (e.g., a spreading ridge or continental rift zone).

drainage basin. The total area from which a stream system receives or drains precipitation runoff.

drift. All rock material (clay, silt, sand, gravel, boulders) transported by a glacier and deposited directly by or from the ice, or by running water emanating from a glacier.

epiclastic rock. A rock formed at Earth's surface by consolidation of fragments of pre-existing rocks.

extrusive. Describes igneous material that has erupted onto Earth's surface.

fault. A break in rock along which relative movement has occurred between the two sides.

feldspar. A group of abundant (more than 60% of Earth's crust), light-colored to translucent silicate minerals found in all types of rocks. Usually white and gray to pink. May contain potassium, sodium, calcium, barium, rubidium, and strontium along with aluminum, silica, and oxygen.

felsic. Describes an igneous rock having abundant light-colored minerals such as quartz, feldspars, or muscovite. Compare to "mafic".

flat slab subduction. Refers to a tectonic plate being subducted beneath another tectonic plate at a relatively shallow angle.

footwall. The mass of rock beneath a fault surface (also see "hanging wall").

formation. Fundamental rock-stratigraphic unit that is mappable, lithologically distinct from adjoining strata, and has definable upper and lower contacts.

fracture. Irregular breakage of a mineral. Any break in a rock (e.g., crack, joint, fault).

gabbro. A group of dark-colored, intrusive igneous rocks. The intrusive equivalent of basalt.

glacial erratic. Boulders transported by glaciers some distance from their point of origin.

granite. A plutonic (intrusive) rock that has large crystals of quartz (10–50%) and potassium and sodium-rich feldspar (65–90%). Mica and amphibole minerals are also common.

granoblastic. Describes the texture of a metamorphic rock in which recrystallization formed crystals of nearly the same size in all directions.

granodiorite. A group of plutonic rocks containing quartz, plagioclase, and potassium feldspar minerals with biotite, hornblende, or, more rarely, pyroxene, as the mafic components.

hanging wall. The mass of rock above a fault surface (also see "footwall").

hornfels. A fine-grained rock composed of a mosaic of same-sized grains without preferred orientation; typically formed by contact metamorphism (metamorphism taking place in rocks at or near the contact with a body of igneous rock).

hypabyssal. An igneous rock formed at a shallow depth.

igneous. Refers to a rock or mineral that originated from molten material; one of the three main classes of rocks—igneous, metamorphic, and sedimentary.

intrusion. A body of igneous rock that invades (pushes into) older rock. The invading rock may be a plastic solid or magma.

joint. A break in rock without relative movement of rocks on either side of the fracture surface.

landslide. Any process or landform resulting from rapid, gravity-driven mass movement.

latite. A porphyritic extrusive volcanic rock having large crystals of plagioclase and potassium feldspar minerals in nearly equal amounts, little or no quartz, and a finely crystalline to glassy groundmass.

lava. Still-molten or solidified magma that has been extruded onto Earth's surface though a volcano or fissure.

left lateral fault. See "strike-slip fault."

leucogranite. A light colored intrusive igneous rock rich in potassium feldspar and aluminum.

lithic. A sedimentary rock or pyroclastic deposit that contains abundant fragments of previously formed rocks.

lithification. The conversion of sediment into solid rock.

lithology. The physical description or classification of a rock or rock unit based on characters such as its color, mineral composition, and grain size.

lithosphere. The relatively rigid outmost shell of Earth's structure, 50 to 100 km (31 to 62 miles) thick, that encompasses the crust and uppermost mantle.

mafic. Describes dark-colored rock, magma, or minerals rich in magnesium and iron. Compare to "felsic."

magma. Molten rock beneath Earth's surface capable of intrusion and extrusion.

mantle. The zone of Earth's interior between the crust and core.

matrix. The fine grained material between coarse (larger) grains in igneous rocks or poorly sorted clastic sediments or rocks. Also refers to rock or sediment in which a fossil is embedded.

metamorphic. Describes the process of metamorphism or its results. One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

metamorphism. Literally, a change in form. Metamorphism occurs in rocks through mineral alteration, formation, and/or recrystallization from increased heat and/or pressure.

metavolcanic. An informal term for volcanic rocks that show evidence of metamorphism.

mid-ocean ridge. The continuous, generally submarine and volcanically active mountain range that marks the divergent tectonic margin(s) in Earth's oceans.

migmatite. Literally, "mixed rock" with both igneous and metamorphic characteristics due to partial melting during metamorphism.

migmatization. The formation of a migmatite.
mineral. A naturally occurring, inorganic crystalline solid with a definite chemical composition or compositional range.
monzonite. A group of plutonic (intrusive igneous) rocks of intermediate color containing approximately equal amounts of alkali feldspar and plagioclase, little or no quartz, and commonly augite as the main mafic mineral. Intrusive equivalent of latite.
moraine. A mound, ridge, or other distinct accumulation of unsorted, unstratified glacial drift, predominantly till, deposited by glacial ice movement.
normal fault. A dip-slip fault in which the hanging wall moves down relative to the footwall.
oceanic crust. Earth's crust formed at spreading ridges that underlies the ocean basins. Oceanic crust is 6 to 7 km (3 to 4 miles) thick and generally of basaltic composition.
orogeny. A mountain-building event.
outcrop. Any part of a rock mass or formation that is exposed or "crops out" at Earth's surface.
paleogeography. The study, description, and reconstruction of the physical landscape from past geologic periods.
Pangaea. A theoretical, single supercontinent that existed during the Permian and Triassic periods.
parent rock. The original rock from which a metamorphic rock was formed. Can also refer to the rock from which a soil was formed.
passive margin. A margin where no plate-scale tectonism is taking place; plates are not converging, diverging, or sliding past one another. An example is the east coast of North America. (also see "active margin").
pebble. Generally, small rounded rock particles from 4 to 64 mm (0.16 to 2.52 in) in diameter.
pelitic. Describes a sedimentary rock composed of clay (pelite) or a metamorphic rock derived by metamorphism of a pelite.
phenocryst. A coarse (large) crystal in a porphyritic igneous rock.
plate tectonics. The concept that the lithosphere is broken up into a series of rigid plates that move over Earth's surface above a more fluid asthenosphere.
platy. Refers to a sedimentary particle whose length is more than 3 times its thickness. Also refers to a sandstone or limestone that splits into thin layers having thicknesses in the range of 2 to 10 mm (0.08 to 0.4 in).
pluton (plutonic). A body of intrusive igneous rock that crystallized at some depth beneath Earth's surface.
porphyry. An igneous rock consisting of abundant coarse crystals in a fine-grained matrix.
potassium feldspar. A feldspar mineral rich in potassium (e.g., orthoclase, microcline, sanidine, adularia).
pumice. Solidified "frothy" lava. It is highly vesicular and has very low density.
pumiceous. Volcanic vesicular texture involving tiny gas holes such as in pumice. Finer than scoriaceous.
pyroclastic. Describes clastic rock material formed by volcanic explosion or aerial expulsion from a volcanic vent; also pertaining to rock texture of explosive origin. In the plural, the term is used as a noun.
pyroxene. A common rock-forming mineral. It is characterized by short, stout crystals.
radiometric age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products.
regression. A long-term seaward retreat of the shoreline or relative fall of sea level.
relative dating. Determining the chronological placement of rocks, events, or fossils with respect to the geologic time scale and without reference to their numerical age.
reverse fault. A contractional high-angle (greater than 45°) dip-slip fault in which the hanging wall moves up relative to the footwall (also see "thrust fault").
rhyodacite. A now-obsolete term for volcanic rock intermediate between rhyolite and dacite.
rhyolite. A group of extrusive volcanic rocks, typically porphyritic and commonly exhibiting flow texture, with phenocrysts of quartz and alkali feldspar in a glassy to cryptocrystalline groundmass. The fine-grained extrusive equivalent of granite.
right lateral fault. See "strike-slip fault."
rock. A solid cohesive aggregate of one or more minerals.
rouche moutonnée. An elongate, eroded ridge or knob of bedrock carved by a glacier parallel to the direction of motion with gentle upstream and steep downstream surfaces.
sandstone. Clastic sedimentary rock of predominantly sand-sized grains.
scarp. A steep cliff or topographic step resulting from displacement on a fault, or by mass movement, or erosion. Also called an "escarpment."
schist. A strongly foliated metamorphic rock that can be readily be split into thick flakes or slabs. Micas are arranged in parallel, imparting a distinctive sheen, or "schistosity" to the rock.
schistose. A rock displaying schistosity, or foliation.
scoria. A bomb-size pyroclast that is irregular in form and generally very vesicular.
scoriaceous. Volcanic igneous vesicular texture involving relatively large gas holes such as in vesicular basalt. Coarser than pumiceous.
seafloor spreading. The process by which tectonic plates pull apart and new lithosphere is created at oceanic ridges.
sediment. An eroded and deposited, unconsolidated accumulation of rock and mineral fragments.
sedimentary rock. A consolidated and lithified rock consisting of clastic and/or chemical sediment(s). One of the three main classes of rocks—igneous, metamorphic, and sedimentary.
shale. A clastic sedimentary rock made of clay-sized particles that exhibit parallel splitting properties.
sierra. An often-used Spanish term for a rugged mountain range.
silt. Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay (1/256 to 1/16 mm [0.00015 to 0.002 in]).
siltstone. A variably lithified sedimentary rock composed of silt-sized grains.
sinistral fault. See "strike-slip fault."
slope. The inclined surface of any geomorphic feature or measurement thereof. Synonymous with "gradient."

sodic. Pertaining to minerals and igneous rocks containing a relatively high proportion of sodium.

stock. An igneous intrusion exposed at the surface; <100 km^2 (40 mi^2) in size.

strata. Tabular or sheet-like masses or distinct layers of rock.

striations. Parallel scratches or lines.

strike. The compass direction of the line of intersection of an inclined surface with a horizontal plane.

strike-slip fault. A fault with measurable offset where the relative movement is parallel to the strike of the fault. Said to be "sinistral" (left-lateral) if relative motion of the block opposite the observer appears to be to the left. "Dextral" (right-lateral) describes relative motion to the right.

subduction zone. A convergent plate boundary where oceanic lithosphere descends beneath a continental or oceanic plate and is carried down into the mantle.

subsidence. The gradual sinking or depression of part of Earth's surface.

tectonic. Relating to large-scale movement and deformation of Earth's crust.

terrane. A large region or group of rocks with similar geology, age, or structural style.

terrestrial. Relating to land, Earth, or its inhabitants.

thrust fault. A contractional dip-slip fault with a shallowly dipping fault surface (less than 45°) where the hanging wall moves up and over relative to the footwall.

till. Unstratified drift, deposited directly by a glacier without reworking by meltwater, and consisting of a mixture of clay, silt, sand, gravel, and boulders ranging widely in size and shape.

topography. The general morphology of Earth's surface, including relief and locations of natural and anthropogenic features.

transcurrent fault. A term for a continental strike-slip fault that does not terminate at lithospheric plate boundaries.

transform fault. A strike-slip fault that links two other faults or two other plate boundaries (e.g. two segments of a mid-ocean ridge). A type of plate boundary at which lithosphere is neither created nor destroyed, and plates slide past each other on a strike-slip fault.

transgression. Landward migration of the sea as a result of a relative rise in sea level.

transpression. A system of stresses that tends to cause oblique shortening (combined shortening and strike-slip).

transpressional fault. A strike-slip fault across which there is a component of shortening.

transtension. A system of stresses that tends to cause oblique extension. Combined extension and strike slip faulting.

trend. The direction or azimuth of elongation of a linear geologic feature.

tuff. Generally fine-grained, igneous rock formed of consolidated volcanic ash.

unconformity. An erosional or non-depositional surface bounded on one or both sides by sedimentary strata that marks a period of missing time.

undercutting. The removal of material at the base of a steep slope or cliff or other exposed rock by the erosive action of falling or running water (such as a meandering stream), of sand-laden wind in the desert, or of waves along the coast.

uplift. A structurally high area in the crust, produced by movement that raises the rocks.

vent. An opening at Earth's surface where volcanic materials emerge.

vesicular. Describes a volcanic rock with abundant holes that formed from the expansion of gases while the lava was still molten.

vitric. Describes pyroclastic material that is characteristically glassy.

volcanic. Describes anything related to volcanoes. Can refer to igneous rock crystallized at or near Earth's surface (e.g., lava).

weathering. The physical, chemical, and biological processes by which rock is broken down.

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Appendix A: Overview of Digital Geologic Data

The following page is an overview of the digital geologic data for Devils Postpile National Monument. For a poster-size PDF of this overview and complete digital data, please see the included CD or visit the Geologic Resources Inventory publications web site (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).

Appendix B: Scoping Summary

The following excerpts are from the GRI scoping summary for Devils Postpile National Monument. The scoping meeting occurred September 25-26, 2002; therefore, the contact information and Web addresses referred to herein may be outdated. Please contact the Geologic Resources Division for current information.

A Geologic Resources Inventory (GRI) workshop was held for Yosemite National Park (YOSE) and Devils Postpile National Monument (DEPO) on September 25-26, 2002. The purpose was to view and discuss the park's geologic resources, to address the status of geologic mapping for compiling both paper and digital maps, and to assess resource management issues and needs. Cooperators from the NPS Geologic Resources Division (GRD), YOSE, DEPO, the University of North Carolina, and the United States Geologic Survey (USGS) were present for the workshop.

This involved field trips to various points of interest in YOSE, led by King Huber, as well as another full-day scoping session to present overviews of the NPS Inventory and Monitoring (I&M) program, the GRD, and the on-going GRI. Round table discussions involving geologic issues for YOSE and DEPO included the status of geologic mapping efforts, interpretation, sources of available data, and action items generated from this meeting. Because of time and logistical limitations, DEPO did not get a site visit during the scoping session.

(The following excerpts involve only Devils Postpile National Monument. Information regarding Yosemite National Park may be found in the Yosemite National Park Geological Resource Evaluation report.)

Existing Geologic Maps and Digital Data

After bibliographies were assembled, a separate search was made for any existing surficial and bedrock geologic maps for YOSE and DEPO. The USGS has published numerous quadrangles in the area at various scales and of variable vintage.

DEPO has a published paper map at 1:62,500 scale (Huber, N.K.; Rinehart, C.D., 1965, Geologic map of the Devils Postpile quadrangle, Sierra Nevada, California, US Geological Survey, GQ-437, 1:62500 scale) that encompasses four 7.5' quadrangles (Mount Ritter, Mammoth Mountain, Crystal Crag, and Cattle Mountain). It is not known whether this map has been digitized at the present time.

However, a more refined map has been produced by the USGS by David Clow and Kenneth Collum. It is not known if this map is published, but it was suggested during the scoping session to use this map instead of GQ-437 for the official park map. Bruce Heise is tracking down more information about this map. It is previewed in "The Story of Devils Postpile: A Land of Volcanic Fire, Glacial Ice and an Ancient River". This publication was released by the Sequoia Natural History Association in 2002.

DEPO Management Needs

Research projects

- Dating of lava flows
- Monitoring glacial polish
- Ground water chemistry of springs in the meadow
- Carbon dioxide flow in the soil and possible tree kill
- Hydrology/geomorphology of San Joaquin River
- Global climate change relative to species diversity (high snowfall now)
- Historic flows of the San Joaquin (contact NPS-Water Resources Division)
- Possible effects to DEPO's springs and watershed from proposed ground water pumping on San Joaquin ridge

Issues/Hazards

- Need climate summary

Geologic Reports

- Huber, N. K. 1987. *The geologic story of Yosemite National Park*. Bulletin 1595. Reston, VA: U.S. Geological Survey.
- Matthes, F. E. 1930. *Geologic history of the Yosemite Valley*. Professional Paper 160. Reston, VA: U.S. Geological Survey.
- Huber, N. K. and Eckhardt, W. W. 2002. *The story of Devils Postpile: A land of volcanic fire, glacial ice and an ancient river*. Three Rivers, CA: Sequoia Natural History Association.

All reports are written for interpretive needs for the park, not technical needs or resource management issues, so would need to be enhanced for the purposes of the GRI report.

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Devils Postpile National Monument
Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2009/160

National Park Service
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Natural Resource Program Center
The Natural Resource Program Center (NRPC) is the core of the NPS Natural Resource Stewardship and Science Directorate. The Center Director is located in Fort Collins, with staff located principally in Lakewood and Fort Collins, Colorado and in Washington, D.C. The NRPC has five divisions: Air Resources Division, Biological Resource Management Division, Environmental Quality Division, Geologic Resources Division, and Water Resources Division. NRPC also includes three offices: The Office of Education and Outreach, the Office of Inventory, Monitoring, and Evaluation, and Office of Natural Resource Information Systems. In addition, Natural Resource Web Management and Partnership Coordination are cross-cutting disciplines under the Center Director. The multidisciplinary staff of NRPC is dedicated to resolving park resource management challenges originating in and outside units of the National Park System.

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