National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Yosemite National Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2012/560

ON THE COVER
Lower Yosemite Fall cascades over granitic rocks in Yosemite Valley, with Half Dome in the background. Photograph © Christine White Loberg.

THIS PAGE
Photographer Matt Melcher awaits his turn to ascend the Half Dome cables about 45 minutes before sunrise. National Park Service photograph by Matt Melcher.

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National Park Service
Geologic Resources Division
PO Box 25287
Denver, CO 80225

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U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado publishes a range of reports that address natural resource topics of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Report Series is used to disseminate high-priority, current natural resource management information with managerial application. The series targets a general, diverse audience, and may contain NPS policy considerations or address sensitive issues of management applicability.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner. This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

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Executive Summary

This report accompanies the digital geologic map data for Yosemite National Park in California, produced by the Geologic Resources Division in collaboration with its partners. It contains information relevant to resource management and scientific research. This report was prepared using available published and unpublished geologic information. The Geologic Resources Division did not conduct any new fieldwork in association with this report.

In 1864, the U.S. federal government set a precedent by granting the "Yo-Semite Valley" and the "Mariposa Big Tree Grove" to the State of California as an "inalienable" public trust. As the first federal grant of land specifically to create a public park, the Yosemite Grant established the foundation upon which the present national park system was built. John Muir and other early conservationists pressed for national park status because of the extraordinary geologic landscape displayed in the Yosemite and Hetch Hetchy valleys and the high peaks of the Sierra Nevada. Yosemite National Park was established on October 1, 1890.

This Geologic Resources Inventory (GRI) report was written for resource managers to assist in resource management and science-based decision making, but it may also be useful for interpretation. The report discusses geologic issues facing resource managers at the park, distinctive geologic features and processes within the park, and the geologic history leading to the park's present-day landscape. An overview graphic illustrates the geologic data; the Map Unit Properties Table summarizes the main features, characteristics, and potential management issues for all the rocks and unconsolidated deposits on the digital geologic map for Yosemite National Park. This report also provides a glossary, which contains explanations of technical, geologic terms, including terms on the map unit properties table. Additionally, a geologic timescale shows the chronologic arrangement of major geologic events, with the oldest events and time units at the bottom and the youngest at the top.

Yosemite National Park is located within the heart of the Sierra Nevada, the largest fault-block mountain range in the United States. Trending northwest–southeast for more than 480 km (300 mi), the Sierra Nevada traverses half the length of California. Comprised of granitic rocks that formed approximately 100 million years ago, the massive block forms an asymmetrical mountain range with a gentle western slope and an eastern edge that rises abruptly from adjacent desert basins, forming a nearly vertical wall of rock that early pioneers found impenetrable.

The iconic landscape of Yosemite Valley includes such world renowned monoliths as Half Dome, El Capitan, and Sentinel Rock. Peaks of the High Sierra decorate the eastern border of the park. Mt. Lyell, the highest peak in Yosemite National Park, rises 3,997 m (13,114 ft) above sea level. The lofty summits of Mt. Dana and Kuna Peak have elevations of more than 3,960 m (13,000 ft).

The sheer cliffs of granite, while magnificent, harbor significant geologic issues that confront the park's resource managers. Rockfalls occur regularly, and many have proven to be deadly. They may be triggered by ground-shaking from earthquakes, intense precipitation, and/or freeze-thaw activity of water in bedrock joints, but many occur without a known cause. Park scientists continue to partner with academic and U.S. Geological Survey geologists to monitor and predict potential rockfalls and to avoid potential rockfall damage to park infrastructure and injuries to staff and visitors.

Seasonal flood events in Yosemite Valley potentially disrupt and damage roads, sewer lines, and other infrastructure. Debris flows and flood events increase erosion and modify river channels and floodplain habitat. Exceptionally damaging winter floods have closed campgrounds and caused extensive property damage.

Global climate change is modifying the intensity and duration of large winter and spring storms, and these changes in storm patterns may increase the intensity and frequency of seasonal flood events. With global warming, modern glaciers in Yosemite National Park are melting at an accelerated rate. The "living glacier" discovered in the Clark Range by John Muir in 1871 is gone. Melting has significantly reduced the Lyell, Dana, and Maclure glaciers; the Lyell Glacier, the second largest in the Sierra Nevada, has lost about 50% of its surface area since 1880. The resulting loss of this natural fresh water reservoir has far-reaching consequences, as the glacier feeds the headwaters of the Tuolumne River, which cascades through the Grand Canyon of the Tuolumne on its way to Hetch Hetchy Reservoir, the controversial impoundment that provides the San Francisco water supply.

Older, Pleistocene-aged glaciers also left geologic features in Yosemite National Park. Some of these features, such as U-shaped valleys, are not in danger of disappearing soon, but smaller scale features, such as glacial polish, are subject to weathering and vandalism. In addition, visitors have pushed some glacial erratics off the domes upon which they once precariously perched. These glacial erratics and more fragile glacial features provide irreplaceable evidence that documents the flow mechanics and physical extent of Yosemite's past alpine glaciers. Preservation of these features allows future generations to experience this dynamic episode of Yosemite's geologic history.

Resource managers also continue to address abandoned mine reclamation issues. In 2010, reclamation of a mine near El Portal mitigated a major source of potential hazardous material. Yosemite National Park does not contain many mines, although some mining structures provide an historical reference to this colorful chapter in Yosemite's history.

A particularly challenging issue facing resource managers concerns the preservation of the intangible values that inspired the creation of Yosemite National Park. The myriad of geologic features present in Yosemite inspired John Muir and other early conservationists with a sense of wonder and a profound appreciation for the American wilderness. Yosemite National Park was designed to connect visitors with the intrinsic values of wilderness treasured by the original advocates for the park. Resource managers face the challenge of preserving this sense of place and providing the approximately 4 million visitors each year with a high-quality visitor experience.

Today, visitors to Yosemite National Park encounter much the same spectacular geologic landscape that inspired John Muir. Shaped by a variety of geologic processes, the geologic features in Yosemite National Park include:

- Granitic, metamorphic, and volcanic bedrock
- Rockfalls, rockslides, and talus piles
- Rock climbing related features
- Joints
- Pleistocene glacial features
- Modern glacial features
- Waterfalls
- Recent geomorphic features

The modern glaciers in the Sierra Nevada are not remnants of the Pleistocene glaciers that carved the granitic rocks into today's landscape of vertical cliffs and U-shaped valleys. The Pleistocene "ice age" glaciers have been absent from the Yosemite National Park region for roughly 10,000 years. As they retreated, these great ice sheets left polished bedrock surfaces, bedrock domes in Tuolumne Meadows, bowl-shaped depressions that have since become mountain lakes, and the impressive pinnacles, spires, and horn-shaped peaks that grace the skyline of the High Sierra. As they melted, they dumped a jumbled mixture of boulders, sand, and clay that had been caught up in the ice. Some of these unconsolidated deposits form ridges that mark episodic glacial retreat. House-sized boulders lay where the glaciers carried them before melting away. The glaciers left a vertical wilderness of cliffs and boulders that is prized by rock climbers around the world.

The Pleistocene glaciers gouged and cut deeply into main valleys that had previously been incised by mountain streams, such as the Merced River. Glacial melt left tributary valleys high on the canyon walls of Yosemite Valley. Their streams form spectacular waterfalls into the valley below that help to define Yosemite National Park. At 739 m (2,425 ft), Yosemite Falls is one of North America's tallest waterfalls. Arguably, Yosemite Falls ranks as North America's best known and most photographed waterfall. The impressive Bridalveil Fall is the first of many waterfalls that visitors see when entering Yosemite Valley from the west.

The glaciers, granitic rocks, and uplift of the Sierra Nevada are only a part of the long history of central California. Metamorphic rocks that border the park to the east and west document sedimentation that occurred 600–500 million years ago, and complex folding and faulting record several deformation events that resulted from the subduction of oceanic seafloor beneath the North American continent. Prior to the emplacement of the granite that became the Sierra Nevada, thick sections of marine sediments and material from volcanic islands erupting offshore were compressed and added to the western margin of North America over millions of years.

In Yosemite National Park, these dynamic tectonic episodes and evidence of Pleistocene glaciers can be seen in the geologic landscape that defined the concept of wilderness for John Muir and continue to stir the human spirit. This human connection to the geologic landscape inspired John Muir and Robert Johnson to design a plan for the area's preservation as a national park. Despite being embroiled in the U.S. Civil War, President Abraham Lincoln understood the need for this park and took the time to establish this cathedral in the mountains of California. Today, Yosemite's resource managers are tasked with preserving the wondrous geologic landscape so important to early champions of the environmental movement and to today's visitors.

Acknowledgements

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The Geologic Resources Division relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

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John Muir, whose vision and perseverance are responsible for the creation of Yosemite National Park. François Matthes and Frank Calkins provided the first detailed research on the geology of the park in 1913. N. King Huber spent a career with the U.S. Geological Survey adding to their research and making the geology of Yosemite National Park accessible to both geologists and non-geologists.

Credits

Author
John Graham (Colorado State University)

Review
Greg Stock (Yosemite National Park)
Jason Kenworthy (NPS Geologic Resources Division)
Rebecca Port (Colorado State University)

Editing
Jennifer Piehl Martinez (Write Science Right)

Report Layout, Formatting, and Production
Rebecca Port (Colorado State University)

Digital Geologic Data Production
Greg Mack (NPS Pacific West Region)
Heather Stanton (Colorado State University)
Stephanie O'Meara (Colorado State University)
Jim Chappell (Colorado State University)
Georgia Hybels (NPS Geologic Resources Division)

Geologic Map Overview Graphics

Layout and Design
Max Jackl (Colorado State University intern)
Georgia Hybels (NPS Geologic Resources Division)

Review
Georgia Hybels (NPS Geologic Resources Division)
Rebecca Port (Colorado State University)
Jason Kenworthy (NPS Geologic Resources Division)
Derek Witt (Colorado State University intern)

Introduction

This section briefly describes the National Park Service Geologic Resources Inventory Program and the regional geologic and historic setting of Yosemite National Park.

Geologic Resources Inventory Program

The Geologic Resources Inventory (GRI) is one of 12 baseline natural resource inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI.

The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (section 204), the 2006 NPS Management Policies, and in the Natural Resources Inventory and Monitoring Guideline (NPS-75). Refer to the "Additional References" section for links to these and other resource management documents.

The objectives of the GRI are to provide geologic map data and pertinent geologic information to support resource management and science-based decision making in more than 270 natural resource parks throughout the National Park System. To realize these objectives, the GRI team undertakes three tasks for each natural resource park: (1) conduct a scoping meeting and provide a scoping summary, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report. These products are designed and written for nongeoscientists. Scoping meetings bring together park staff and geologic experts to review available geologic maps, develop a geologic mapping plan, and discuss geologic issues, features, and processes that should be included in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan into digital geologic map data in accordance with their data model. Refer to the "Geologic Map Data" section for additional map information. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the geologic report. This geologic report assists park managers in the use of the map, and provides an overview of the park geology, including geologic resource management issues, geologic features and process, and the geologic history leading to the park's present-day landscape.

For additional information regarding the GRI, including contact information, please refer to the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/). The current status and projected completion dates for GRI products are available on the GRI status website (http://www.nature.nps.gov/geology/GRI_DB/Scoping/Quick_Status.aspx).

Regional Landscape

Yosemite National Park (fig. 1) preserves an extraordinary and powerful landscape that defines the concept of wilderness for many visitors. Sheer granitic cliffs and domes, pristine alpine meadows, deep glacial valleys, spectacular waterfalls, and expansive vistas of the majestic High Sierra compose the park's 302,687 ha (747,956 ac), which is about the size of Rhode Island. Nearly 95% of Yosemite National Park's area is designated wilderness. In 1984, 130 km (83 mi) of the Tuolumne River was designated as part of the Wild and Scenic River System, and three years later, 130 km (81 mi) of the Merced River was added to the system. Massive giant sequoias (*Sequoiadendron giganteum*), trees that can live more than 3,000 years, grow in three groves within the park.

The creation of Yosemite National Park was as unique as its world-renowned features. In 1864, three years into the Civil War, the U.S. federal government responded to public pressure and granted the "Yo-Semite Valley" and the "Mariposa Big Tree Grove" to the State of California as an inalienable public trust. The Yosemite Grant, the first federal grant of land specifically for a public park, laid the groundwork for the present national park system. Eight years later, Yellowstone National Park became our first national park.

Located in California's Sierra Nevada, the park's cliffs rise 900–1,200 m (3,000–4,000 ft) above the floor of Yosemite Valley. Only 11 km (7 mi) long and approximately 1.6 km (1 mi) wide, Yosemite Valley offers an overwhelming display of cascading cataracts amid such geologic marvels as El Capitan, Cathedral Rocks, Three Brothers, Sentinel Rock, and Half Dome (fig. 2). The three sections of Yosemite Falls combine to make it the fourth tallest waterfall in North America. Bridalveil Fall (fig. 3), the first waterfall visitors see upon entering Yosemite Valley, plunges 190 m (620 ft) to the valley floor (National Park Service 2010a). John Muir, whose name is synonymous with Yosemite National Park, described the valley in 1912:

> *The walls are made up of rocks, mountains in size, partly separated from each other by side cañons, and they are so sheer in front, and so compactly and harmoniously arranged on a level floor, that the Valley, comprehensively seen, looks like an immense hall or temple lighted from above…Down through the middle of the Valley flows the crystal Merced, River of Mercy, peacefully quiet…as if into this one mountain mansion Nature had gathered her choicest treasures…* John Muir (1912, p. 4–5)

Park Map

Area Map

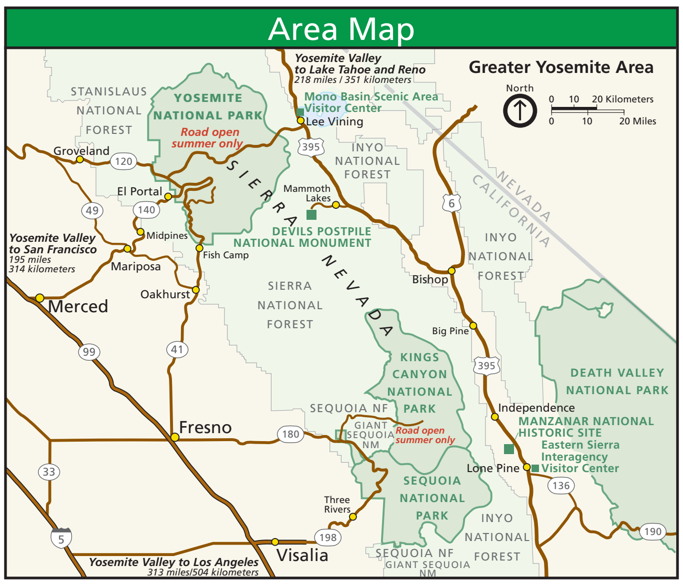
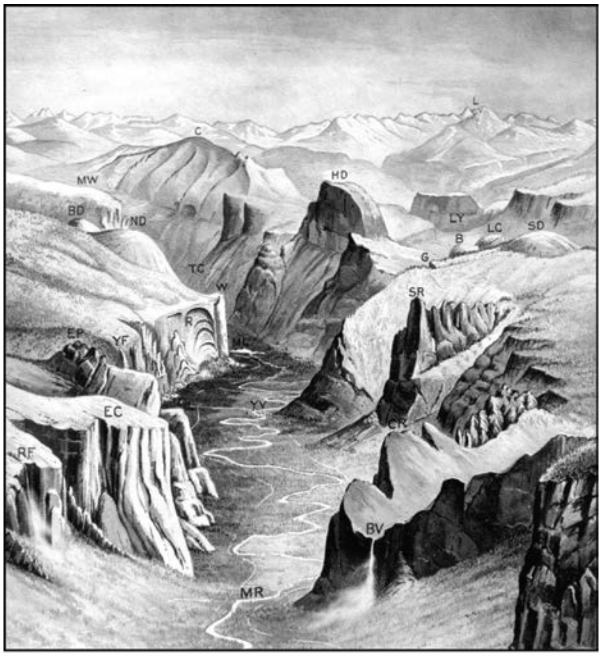


Figure 1. Yosemite National Park maps. Located approximately 314 km (195 mi) from San Francisco, Yosemite National Park preserves granitic cliffs, waterfalls, clear streams, giant sequoias, and abundant biological diversity. National Park Service maps.

Yosemite Valley Map



RF: Ribbon Fall	C: Clouds Rest
EC: El Capitan	HD: Half Dome
EP: Eagle Peak	L: Mount Lyell
YF: Top of Yosemite Falls	LY: Little Yosemite
YV: Yosemite Village	LC: Liberty Cap
R: Royal Arches	B: Mount Broderick
W: Washington Column	SD: Sentinel Dome
TC: Tenaya Canyon	G: Glacier Point
ML: Mirror Lake	SR: Sentinel Rock
ND: North Dome	CR: Cathedral Rocks
BD: Basket Dome	BV: Bridalveil Fall
MW: Mount Watkins	MR: Merced River

Figure 2. Bird's-eye view to the east of Yosemite Valley and the High Sierra. Illustration from photographs by C.A. Weckerly included in François Matthes' classic study of Yosemite Valley, U.S. Geological Survey Professional Paper 160 (Matthes 1930, plate 15). The legend is organized geographically, proceeding clockwise from the lower left corner of the illustration. U.S. Geological Survey photographic library, available at http://libraryphoto.cr.usgs.gov/htmllib/batch67/batch67j/batch67z/mfe00159.jpg (accessed November 15, 2010).

The Sierra Nevada (Spanish for "snowy mountain range") is the largest fault-block mountain range in the United States, traversing northwest-southeast along half the length of California [more than 480 km (300 mi)]. The massive block of crust was uplifted along a northwest-trending fault system now forming the border between the mountain range and the basins to the east. The High Sierra refers to the 40-km (25-mi)-wide, rugged central plateau of the Sierra Nevada that extends approximately 160–260 km (100–160 mi) north from Mt. Whitney (Raub et al. 2006).

Peaks of the High Sierra line the park's eastern border. Mount Lyell, the highest peak in Yosemite National Park, rises 3,997 m (13,114 ft) above sea level. Elevations of Mt. Dana and Kuna Peak surpass 3,960 m (13,000 ft). An additional eighteen named and several unnamed peaks rise above 3,660 m (12,000 ft). Mt. Hoffman, at an elevation of 3,307 m (10,850 ft), lies in the approximate geographic center of the park. In Sequoia and Kings Canyon National Parks to the south, Mount Whitney's summit [4,417 m (14,491 ft)] forms the highest elevation in the contiguous United States.

Approximately 65–130 km (40–80 mi) wide, the Sierra Nevada has a long, gentle western slope and an incredibly steep eastern escarpment that rises abruptly, along a normal fault system, from the Owens and Mono basins (fig. 4). For example, over a straight-line horizontal distance of about 13 km (8 mi), the elevation changes nearly 1,000 m (3,300 ft) from 2,067 m (6,781 ft) at Lee Vining, California, on the shores of Mono Lake, to 3,031 m (9,943 ft) at the Tioga Pass entrance station. Before the road was paved, this trip up the eastern face of the Sierra Nevada presented a mixture of white-knuckle driving and fantastic scenery. The paved road has removed the driving challenge, but the unsurpassed scenery remains.

Overview of Yosemite's Geology

Of the three main categories of rock (igneous, sedimentary, and metamorphic), igneous rocks are most common at Yosemite National Park, including the granitic salt-and-pepper-colored rocks that form such features as Half Dome, El Capitan, and the cliffs of Yosemite Valley (fig. 5). The park's granitic rocks can be classified more specifically as granite, granodiorite, and tonalite (fig 6). These plutonic (intrusive) igneous rocks formed when magma (molten rock) cooled and solidified within Earth's crust, and thus contain individual crystals and primary minerals that are often visible to the unaided eye. In contrast, volcanic (extrusive) igneous rocks form when magma cools and solidifies rapidly on Earth's surface. Because rapidly-cooling crystals have less time to grow, most mineral grains in volcanic rocks are too small to be distinguished without a microscope.

Plutons (large, discrete masses of plutonic rock) form the 100-km (40-mi)-wide Sierra Nevada Batholith (from the Greek words bathos, deep, and lithos, rock), the core of the Sierra Nevada. More than 100 plutons representing separate episodes of magma intrusion and solidification shape the batholith in the vicinity of Yosemite National Park (Hamilton 1978; Huber 1989). Once thought to have originated as a simple emplacement of magma, the Sierra Nevada Batholith is now known to record a complex history of pluton emplacement associated with subduction zone volcanism that took place 220–85 million years ago during the Mesozoic era, although the majority of granites in Yosemite National Park are between 105 and 85 million years old (Bateman 1992; Glazner and Stock 2010).

Most granitic rocks in Yosemite National Park are medium to coarse grained with crystals that are relatively equal in size. However, some units contain larger mineral crystals, called phenocrysts, scattered in a surrounding groundmass of smaller crystals. The Cathedral Peak Granite (map unit Kcp), for example, includes characteristically large orthoclase (potassium) feldspar phenocrysts among smaller crystals of quartz, feldspar,

Figure 3. Bridalveil Fall, one of many waterfalls in Yosemite National Park, plummets 190 m (620 ft) to the floor of Yosemite Valley. View is from Rainbow Point. National Park Service photograph courtesy of Greg Stock (Yosemite NP).

and biotite that comprise the groundmass. Rock climbers utilize the larger mineral crystals as hand and foot holds.

Although Proterozoic- and Paleozoic-age sedimentary rocks are exposed in the White and Inyo mountains, east of the Sierra Nevada Batholith, all sedimentary rocks in Yosemite National Park have been metamorphosed, or transformed by increasing heat and pressure to form new minerals or fuse individual mineral grains. If the original rock type is known, these metamorphic units may be identified by the prefix "meta."

Linear, northwest-trending belts of metasedimentary and metavolcanic rock outcrop along the western and eastern borders of Yosemite National Park (Huber 1989; Huber et al. 1989; Bateman 1992). The western metamorphic belt contains strongly-deformed, weakly-metamorphosed rocks that range in age from about 500 million years (Early Cambrian) to approximately 150 million years (Upper Jurassic). Tectonic plate collisions during the Paleozoic and Mesozoic transported these units from their original deep-marine depositional sites and compressed them onto the western margin of North America. In contrast, the metavolcanic and metasedimentary rocks east of the Sierra Nevada Batholith have not been displaced very far from their original sites of deposition. A few remnants of metamorphic rocks also lie within the batholith and provide clues to deformation in central California prior to batholith emplacement (Schweickert and Lahren 1991).

The andesitic lava of Little Devils Postpile, located along the Tuolumne River in Yosemite National Park, solidified about 8 or 9 million years ago and attests to volcanic activity that occurred prior to Pleistocene glaciation (Huber 1989; Glazner and Stock 2010).

Figure 4. Peaks abruptly rise nearly 3 km (2 mi) from the relatively flat Owens Valley (foreground) along the eastern escarpment of the Sierra Nevada. View is looking west at Olancha Peak. U.S. Geological Survey photograph by R.M. Campbell in 1901, available at http://libraryphoto.cr.usgs.gov/htmllib/btch515/btch515j/btch515z/cmr00234.jpg (accessed June 1, 2012).

Period	Epoch	Intrusive Suite	Rock Unit (map symbol)	General Description
Cretaceous (145.5–65.5 Ma*)	Upper		Aplite and pegmatite (Kapp)	Medium- to fine-grained with feldspar and quartz phenocrysts. Dikes and small masses of aplite and pegmatite.
		Tuolumne	Johnson Granite Porphyry (Kjp)	
			Cathedral Peak Granodiorite (Kcp)	
			Half Dome Granodiorite (Khd)	
			Granodiorite of Kuna Crest (Kkc)	
			Sentinel Granodiorite (Ks)	Coarse-grained; dark gray; sphene.
			Yosemite Creek Granodiorite (Kyc)	Medium- to coarse-grained.
		Sonora Pass	Granodiorite of Topaz Lake (Ktz)	Medium-grained; some large feldspar phenocrysts.
			Granodiorite of Kinney Lakes (Kkl)	
		John Muir	Quartz Monzonite of Rock Creek Lake (Krc)	Fine- to medium grained.
			Granodiorite of Lake Edison (Kle)	Medium-grained with sphene.
			Mount Givens Granodiorite (Kmg)	Medium- to coarse-grained.
		Jack Main Canyon	Granodiorite of Boundary Lake (Kblg)	Medium- to coarse-grained; light colored to dark-gray; locally porphyritic.
			Granodiorite of Lake Vernon (Klv)	
			Granodiorite of Bearup Lake (Kbu)	
			Quartz Diorite of Mount Gibson (Kgi)	
	Lower	Washburn Lake	Granite Porphyry of Cony Crags (Kcc)	Medium-grained with sparse phenocrysts of plagioclase, quartz, and potassium feldspar.
			Granite of Tuner Lake (Ktl)	
			Granodiorite of Red Devil Lake (Krd)	
		Buena Vista Crest	Granite of Chilnualna Lakes (Kcl)	Fine- to medium-grained with some potassium-feldspar phenocrysts and dark, irregular masses.
			Bridalveil Granodiorite (Kbv)	
			Granodiorite of Breeze Lake (Kbz)	
			Granodiorite of Ostrander Lake (Kol)	
			Granodiorite of Illilouette Creek (Kic)	
			Quartz Diorite (Kid)	
		Merced Peak	Granite of Timber Knob (Ktk)	Fine- to medium grained; variable composition.
			Granodiorite of Jackass Lake (Kjl)	
			Granite Porphyry of Shellenbarger Lake (Ksl)	Fine- to medium-grained.
			Granite of Grace Meadow (Kgm)	Medium- to fine-grained.
		Yosemite Valley	Taft Granite (Ktg)	Fine- to coarse-grained; feldspar and quartz phenocrysts.
			El Capitan Granite (Kec)	
			Granodiorite of Beasore Meadow (Kbe)	Mafic; granodiorite and tonalite.
			Granite of Shuteye Peak (Ksp)	Light gray; feldspar phenocrysts.
			Granodiorite of Bummers Flat (Kbf)	Medium-grained; phenocrysts.
			Granite of Bond Pass (Kbop)	Moderately foliated.
			Granite Porphyry of Star Lakes (Kst)	Medium- to fine-grained.
		Fine Gold	Granodiorite of Arch Rock (Kar)	Medium-grained; poikilitic feldspar.
			Bass Lake Tonalite (Kblt)	
			Granite of Dorothy Lake (Kdl)	Light-pink; tourmaline-bearing.
			Granodiorite of Lake Harriet (Klh)	Dull-gray; biotite, hornblende.
Jurassic (199.6–145.5 Ma)	Upper		Diorite and Gabbro (KJqdg)	Small, irregular-shaped bodies.
	Middle		Tonalite of Granite Creek (Jgc)	Medium-grained.
	Lower	Lower Jurassic plutons are absent in the Yosemite area.		
Triassic (251–199.6 Ma)	Upper	Scheelite	Wheeler Crest Granodiorite (TRwc)	Medium-grained granite, commonly porphyritic.
			Granite of Lee Vining Canyon (TRlv)	

**** Age is in millions of years before present and indicates the time spanned by associated epoch or period. Rock/sediment units associated with those epochs or periods may not encompass the entire age range.***

Figure 5. Simplified stratigraphic column illustrating units of Mesozoic plutonic, primarily granitic rocks mapped in the Yosemite National Park region. Units are from Huber et al. (1989). An intrusive suite includes plutons related in time and space. Units not in an intrusive suite are discrete plutons. Colors are standard colors approved by the U.S. Geological Survey to indicate different time periods on geologic maps; they also correspond to the colors on the Map Unit Properties Table. See the Map Unit Properties Table and the "yose_geology.pdf" included in the GIS data for a more complete list and description of all units present in Yosemite National Park and vicinity.

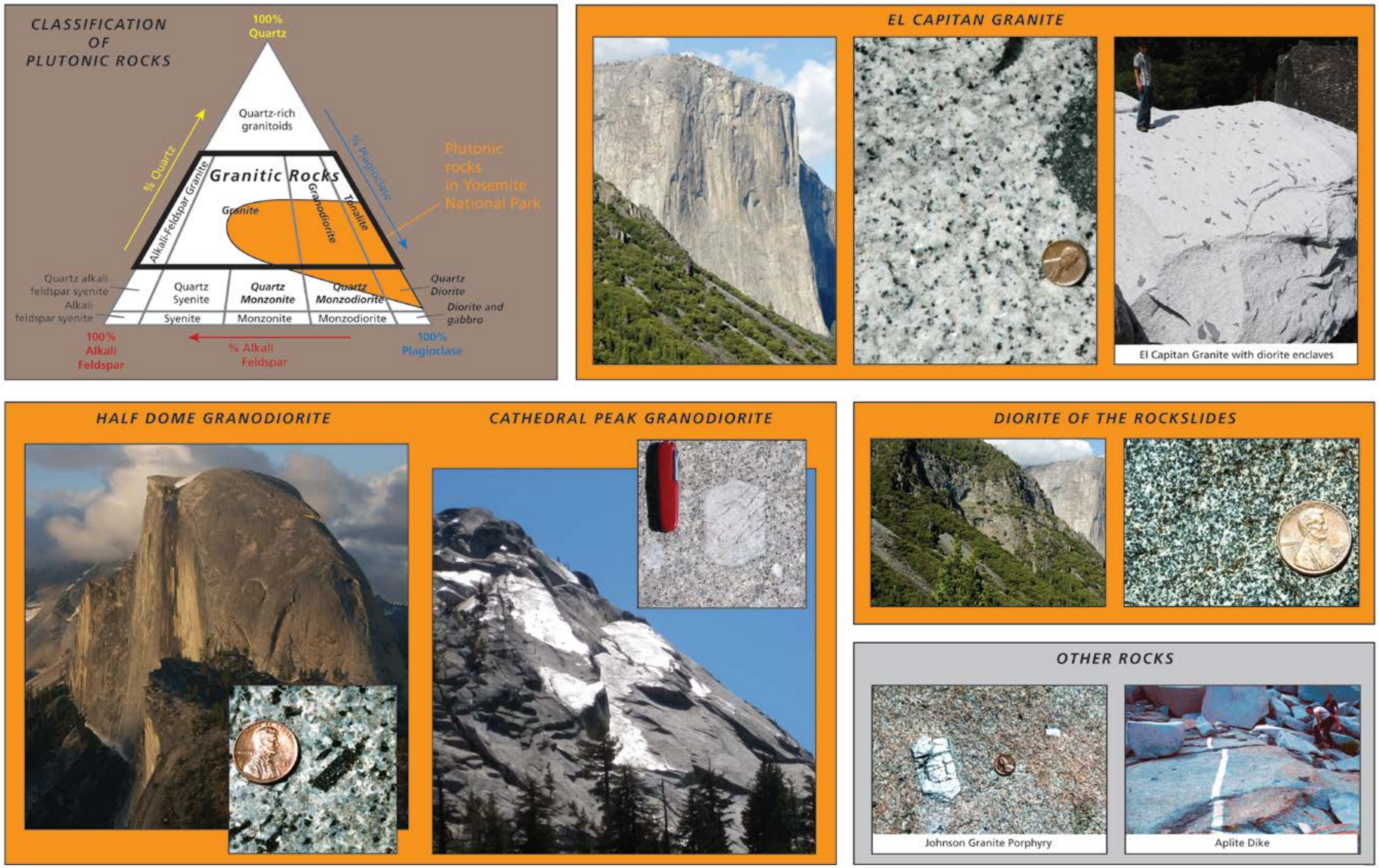


Figure 6. Plutonic Rocks of Yosemite National Park. Classification of Plutonic Rocks diagram adapted from Huber (1989, fig. 9) by Jason Kenworthy (NPS Geologic Resources Division) and Rebecca Port (Colorado State University). Photographs courtesy of Greg Stock, Yosemite National Park and from Huber (1989), available at http://www.yosemite.ca.us/library/geologic_story_of_yosemite/ (accessed March 25, 2012).

The impressive columnar joints of the Postpile represent solidified magma in a conduit that once fed an ancient volcano.

In the Cenozoic, the Sierra Nevada Batholith was uplifted and tilted to the west, allowing ice age alpine glaciers to carve these dense, hard plutonic rocks into the iconic landscape seen today in Yosemite National Park. The cirque basins, alpine lakes, U-shaped and hanging valleys, polished granitic domes, spectacular waterfalls, unusual glacial erratics, glacial moraines, and other glacial features originated in the dynamic processes of Pleistocene (ice age) glaciers that first impacted the region about 1.5 million years ago (Glazner and Stock 2010). Glaciers straightened, deepened, and widened previously stream-cut valleys and filled them with sediment. Most of the glacial features in the park reflect the most recent major episode of glaciation, called the Tioga, which began about 26,000 years ago and reached its maximum extent about 18,000 years ago (Huber 1989; Glazner and Stock 2010). The scoured cliffs in Yosemite National Park contrast sharply with the jagged peaks, spires, and pinnacles that stood above the glacial ice.

The joints (fractures) in the park's granitic bedrock significantly influenced glacial activity in this otherwise homogeneous, erosion-resistant landscape. Glaciers plucked and gouged highly-jointed granitic bedrock much more easily than massive, relatively joint-free plutons (Dünhforth et al. 2010). Yosemite National Park contains three primary joint patterns: two nearly vertical and perpendicular joint sets that trend northwest and northeast and exfoliation joints that form parallel, sheet-like layers on the surface of granitic exposures. These joints not only influence modifications in the park's landscape, but also pose potential safety hazards by triggering rockfalls.

The modern glaciers in the Sierra Nevada are not remnants of Pleistocene glaciation, but are the product of post-Pleistocene (Neoglacial) events. Warming temperatures at the end of the Pleistocene and beginning of the Holocene (11,000 years ago) reached a maximum about 5,000 years ago, when most, if not all, glaciers in the Sierra Nevada had melted. Since then, global climate has fluctuated through relatively minor warming and cooling cycles. Covering slightly more than 1.3 km^2 (0.5 mi^2), the Palisades Glacier is the largest glacier in the Sierra Nevada. The Lyell Glacier in Yosemite National Park [0.65 km^2 (0.25 mi^2)] is the second largest glacier in the Sierra Nevada (Huber 1989). Although nowhere near the volume of the Pleistocene (ice-age) glaciers, Yosemite's modern glaciers may have been near their maximum extent in 1871, when John Muir hiked through Yosemite Valley and into the high country to begin his study of Yosemite's glaciers.

The Sierra Nevada continues to rise. Today, the estimated rate of uplift at Mount Dana is about 4 cm (1.5 in) per 100 years, which exceeds the rate of beveling by erosion, resulting in a net increase in elevation (Huber 1989). Rockfalls continue to modify canyon walls while rivers incise valley floors. Sediment slowly fills alpine lakes, and cirque glaciers, although melting at a rapid rate, continue to add material to terminal moraines while scouring and polishing bedrock. From its granitic domes and waterfalls to its sediment-filled valleys, Yosemite National Park exhibits the past processes of plate tectonics and glaciation along with ongoing weathering and erosion that continue to shape one of America's most impressive landscapes.

Park History

Traversing more than half the length of California with peaks over 3,900 m (13,000 ft) high, the Sierra Nevada presented a formidable barrier to early pioneers venturing into California from the east. On their arduous journey, few pioneers made efforts to climb mountains and explore the landscape. In the 1830s, Joseph Walker and his fellow trappers were probably the first men of European descent to view Yosemite Valley. Walker climbed the eastern escarpment and crossed the Sierra Nevada in 1833. A printshop fire in 1839 destroyed most copies of his journal, so his record of magnificent waterfalls and giant trees went unread for years (Huber 1989; Kiver and Harris 1999).

In 1848, the discovery of gold near Coloma, California, about 175 km (110 mi) from the northernmost point of Yosemite National Park, brought a horde of miners to Sierra Nevada foothills. Mining brought confrontations with local Miwok and Paiute Indians. In 1851, one year after California entered the Union, Maj. James Savage and the Mariposa Battalion of militia pursued 200 Indians of the Ahwaneechee tribe, led by Chief Tenaya, into Yosemite Valley (Palmer 1997; Kiver and Harris 1999). Awestruck by the extraordinary beauty of the valley, Dr. Lafayette Bunnell, the troop's physician, suggested they call it Yo-sem-i-ty (meaning "grizzly bear") after the Indian tribe inhabiting it (an alternative view is that Bunnell named it Yosemite, an Anglicization of Uzumati) (Huber 1989; Palmer 1997). One year later, the giant sequoias about which Walker had written were rediscovered in the Mariposa Grove and in the Calaveras Grove north of Yosemite.

In the mid-1850s, San Francisco's James Hutchings began bringing artists, tourists, and photographers to the area. He developed tourist facilities and hired a young, Scottish-born naturalist and handyman named John Muir in 1868 (Kiver and Harris 1999). In 1863, Josiah Whitney, the Director of the California Geological Survey, explored the headwaters of the Tuolumne River and named Mounts Dana, Lyell, Maclure, and Hoffmann (Huber 1989). The first three were named for famous geologists while Mount Hoffmann was named for Charles Hoffmann, one of Whitney's men. In 1867, another survey team ascended Mount Hoffmann (fig. 7). Data from these trips and additional topographic mapping by survey colleagues Clarence King and James Gardiner provided the first realistic descriptions of Yosemite Valley (Russell 1947; Huber 1989).

Figure 7. Charles F. Hoffmann on Mount Hoffmann. Hoffmann stands at the transit below the summit of the peak that would later be named in his honor. Composed of the Granodiorite of Mount Hoffman (map unit Kmh), the exposure contains abundant joints and fractures. Photograph by W. Harris, 1867, first published in J. D. Whitney's *The Yosemite Book* (1868) and included in N. King Huber's *The Geologic Story of Yosemite National Park* (1989, fig. 3), available at http://www.yosemite.ca.us/library/geologic_story_of_yosemite/images/3.jpg (accessed November 22, 2010).

Public pressure spread to preserve the Yosemite region from overdevelopment, and although preoccupied with the Civil War, President Abraham Lincoln signed a bill granting Yosemite Valley and Mariposa Grove to California in 1864. Camped by Soda Springs in 1889, twelve years after the establishment of Yellowstone National Park, John Muir, who would become the premier spokesman for the park, and Robert Underwood Johnson, editor of the influential *The Century Magazine*, hatched the concept of Yosemite National Park (Glazner and Stock 2010).

In 1890, Congress honored Muir's recommendations and established Yosemite as the nation's third national park, but it did not include Yosemite Valley. Muir and other conservationists founded the Sierra Club in 1892 and continued lobbying Congress to transfer Yosemite Valley and the Mariposa Grove to federal control. In an exceptional move to garner support, Muir took President Theodore Roosevelt on a 3-day back-country camping trip in Yosemite in 1903 (fig. 8). Two years later, Congress and California worked together to adjust the park's boundaries to include Yosemite Valley and the Mariposa Grove.

In 1913, the U.S. Geological Survey sent François E. Matthes and Frank C. Calkins into the Yosemite area to study the geomorphology and glacial geology and the bedrock geology, respectively. Their exceptional descriptions and interpretations of the region continue to provide a foundation upon which geologists build their research.

Despite the inclusion of the Yosemite Valley and Mariposa Grove, mining and logging interests reduced the size of Yosemite National Park in 1905 by more than 1,295 km^2 (500 mi^2), including land now encompassed by Devils Postpile National Monument (Graham 2009). A second, more serious threat to the park began as early as 1890 when San Francisco officials decided that Hetch Hetchy Valley was an excellent site for a dam and reservoir.

Muir considered Hetch Hetchy Valley, with its waterfalls and 610-m (2,000-ft) high cliffs, to be a second Yosemite Valley. He described it as "a grand landscape garden, one of Nature's rarest and most precious mountain temples" (Muir 1912, p. 191). For 23 years, John Muir, the Sierra Club, and other supporters fought to keep Hetch Hetchy Valley a wilderness. Their efforts failed. In 1913, Congress passed, and President Woodrow Wilson signed, the Raker Bill, allowing the construction of O'Shaughnessy Dam and the flooding of Hetch Hetchy Valley. John Muir died in 1914 and never witnessed the inundation of the valley, which began in 1923 upon completion of the dam.

In Yosemite Valley, John Muir sought the solitude and serenity found in wildness. Today, nearly 95% of Yosemite National Park is designated wilderness. Roughly 4 million visitors visit the park each year, and away from the roadways and well-traveled paths, a hiker can still enjoy the landscape and wildness that inspired John Muir.

Figure 8. President Theodore Roosevelt and John Muir on a 1903 camping trip in Yosemite. National Park Service photograph.

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping meeting for Yosemite National Park 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 those discussions and highlights particular issues that may require attention from resource managers. Contact the Geologic Resources Division for technical assistance.

The grandeur of Yosemite National Park is centered on its geologic landscape, but resource managers also face a variety of daunting geologic issues. Rockfalls and rockslides are especially hazardous in Yosemite Valley. Potential geologic hazards and issues relevant to Yosemite National Park include:

- Rockfalls, rockslides, and rock avalanches;
- Seismic activity (earthquakes);
- Debris flows, flooding, and erosion;
- Protection of glacial features;
- Reclamation of abandoned mines;
- Global climate change; and
- Preservation of the geologic landscape.

Yosemite National Park also supports a considerable variety of scientific research projects and is a world renowned geologic research area. Geologic research ranges from studies of Yosemite's granitic rocks to those of the dynamic modern glaciers in the High Sierra. Ongoing research by park geologists and geologists from academic institutions and the U.S. Geological Survey focuses on unstable cliffs and conditions that may lead to future rockfalls.

Rockfalls, Rockslides, and Rock Avalanches

Rockfalls, rockslides, and rock avalanches are the most powerful current geologic processes in the Yosemite National Park; they play a major role in shaping the park's magnificent cliffs and canyons (National Park Service 2011a). These natural processes also pose significant visitor safety and maintenance issues for park management, especially in Yosemite Valley. About 50 slope failures occur each year in Yosemite National Park, with an average of about one per week (Stock et al. 2012a; Zimmer et al. 2012). As of 2011, 15 deaths and at least 70 injuries due to rockfalls and other mass movement events had been documented in the park (Stock et al. 2012a).

Rockfalls and rockslides are similar, but geologists define rocks that primarily fall down a vertical cliff as a 'rockfall' and rocks that slide down a slope as a 'rockslide.' Rock avalanches are massive rockfalls that become flows across the ground surface and attain great velocity. Whereas rockfall debris accumulates at the bases of cliffs, forming wedge-shaped deposits known as talus slopes or talus piles, debris from rock avalanches extends much farther into the valley. The El Capitan Meadow rock avalanche, for example, extends almost 670 m (2,200 ft) into Yosemite Valley from the base of El Capitan (Glazner and Stock 2010; Stock and Uhrhammer 2010). In this report, "rockfall" is used as an inclusive term for any downward movement of rocks under the influence of gravity.

This report provides a brief overview of the history of rockfall in the park; rockfall triggers; rockfall inventory, monitoring, and research efforts in the park. Refer to the park's rockfall webpage for more detailed information and publications: http://www.nps.gov/yose/nature science/rockfall.htm (accessed July 26, 2012).

In response to the first quantitative assessment of rockfall risk in Yosemite Valley (Stock et al. 2012a), the park closed cabins and concessionaire employee housing in Curry Village during June 2012, as this GRI report was being prepared. Combined with Curry Village closures in 2008, the park has reduced to overall risk to structures in Yosemite Valley by 95% (National Park Service 2012).

Rockfall History

More rockfalls have been documented in Yosemite National Park than in any other national park. These events happen every year in Yosemite National Park; in 2010, 59 rockfalls occurred while 53 occurred in 2011 (National Park Service 2011a). As this report was being prepared, a rockfall closed Big Oak Flat Road on January 24, 2012, and more such events will likely occur before this report is printed (fig. 9). Rockfalls are responsible for the Rockslides, a prominent geologic feature adjacent to El Capitan in Yosemite Valley. Examples of large, recent rockfalls at El Capitan, Yosemite View Lodge, Ahwiyah Point, Glacier Point, Happy Isles, Middle Brother, and Cookie Cliff, are summarized here to illustrate their impacts on park infrastructure and visitor safety.

On October 11, 2010, dust rising from the impact of three rockfalls from El Capitan could be seen throughout Yosemite Valley. With an estimated volume exceeding 1,000 m^3 (35,000 ft^3) or roughly 100 dump truck loads, this rockfall event was the largest in the park in 2010 (National Park Service 2011a). Boulders from this rockfall cluster did not damage trails or roads, but a rockfall of Bass Lake Tonalite (map unit Kblt) in December 2010 temporarily closed Highway 140 about 1 km (0.5 mi) east of Yosemite View Lodge in El Portal.

Figure 9. Rockfall closed the Big Oak Road (Highway 120) in January 2012. National Park Service photograph.

On March 28, 2009, blocks of Half Dome Granodiorite (map unit Khd) fell approximately 550 m (1,800 ft) from Ahwiyah Point near Half Dome, buried a major portion of the Mirror Lake Loop Trail (fig. 10), and damaged the Ahwahnee Hotel parking area. The ground shaking that resulted from the impact was equivalent to a magnitude 2.4 earthquake. The volume of the Ahwiyah rockfall was approximately 46,700 m^3 (1,650,000 ft^3), making it the largest rockfall in Yosemite National Park since the 1987 Middle Brother event (Zimmer et al. 2012).

The Middle Brother rockfall, the largest rockfall in Yosemite National Park in historic time, generated a volume of 600,000 m^3 (21,200,000 ft^3), or about 65,000 dump truck loads of rock, on March 10, 1987 (Wieczorek et al. 1989; National Park Service 2009a; Glazner and Stock 2010). A portion of Sentinel Granodiorite (map unit Ks) and El Capitan Granite (map unit Kec) broke loose and fell 790 m (2,600 ft) to the valley floor. The rock mass shattered as it fell, and boulders rained down on Northside Drive and on the opposite banks of the Merced River. Smaller rockfalls preceding the main event had caused park officials to close Northside Drive, preventing serious injuries. However, more than 3 m (10 ft) of rock buried several hundred feet of Northside Drive. The road was reopened two months later (Glazner and Stock 2010).

Figure 10. The Ahwiyah Point rockfall on March 28, 2009, sent 43,000 m^3 (1,500,000 ft^3) of Half Dome Granodiorite (map unit Khd) tumbling toward the historic Ahwahnee Hotel. The rockfall was the largest in the park since the 1987 Middle Brother rockfall, in which 600,000 m^3 (21,200,000 ft^3) of rock fell into the valley. Inset photo shows damage to the Mirror Lake loop trail. National Park Service photograph courtesy of Greg Stock (Yosemite NP).

On October 7 and 8, 2008, two rockfalls originating in Glacier Point Granodiorite (Stock et al. 2011) led to the permanent closure of 233 visitor accommodations and 43 concessioner employee housing units in the historic Curry Village area, which lies at the base of sheer granitic walls composed of Glacier Point and Half Dome granodiorites (map units Kglp and Khd; National Park Service 2008a). Prehistoric rockfalls had left boulders scattered throughout Curry Village prior to the construction of the modern cabins, and rockfalls from Glacier Point had occurred in 1998 and 1999. On November 16, 1998, 563 m^3 (19,872 ft^3) of rock fell from the north-facing wall of Glacier Point, endangering employees and visitors at Camp Curry. Some of the larger rocks reached within about 23 m (75 ft) of the tent cabins on the talus slope. Smaller-volume rockfalls in 1999 killed one climber and injured two others (Wieczorek and Snyder 1999).

The Happy Isles rockfall that occurred in the evening of July 10, 1996, produced an unusual hazard. A rock slab estimated to be about 5.5 m (18 ft) thick and the length of a football field detached from the cliff above Happy Isles, fell onto an inclined surface, slid approximately 240 m (800 ft), and was launched into free- fall for another 550 m (1,800 ft). The slab hit the talus slope at the base of the cliff at about 430 km per hour (270 mph) and generated an air blast with wind speeds exceeding 400 km per hour (250 mph) (Wieczorek et al. 2000; Glazner and Stock 2010). By comparison, Hurricane Katrina's wind speed at landfall in Louisiana on August 29, 2005, was 201 km per hour (125 mph). The force of the blast from the Happy Isles rockfall destroyed trees up to 90 m (300 ft) away and embedded rock fragments into tree trunks more than 150 m (500 ft) from the rockfall (Glazner and Stock 2010). One visitor was killed and several others injured by falling trees.

On April 3, 1982, after an exceptionally wet winter, an enormous section of El Capitan Granite (map unit Kec) separated from the northern part of Cookie Cliff and slid into the Merced River. Rock debris from the Cookie Cliff rockslide covered more than 150 m (500 ft) of El Portal Road, severed sewage pipes, and destroyed the telephone line. Effluent flowed into the river for several days, and the road was closed for several weeks as road crews blasted and removed boulders weighing as much as 20,000 tons (Glazner and Stock 2010).

Rockfall Triggers

The rockfalls in Yosemite National Park result from a variety of triggering events. Precipitation, in the form of rain and/or snow meltwater, triggers many rockfalls (Wieczorek and Jäger 1996; Stock et al. 2012a, 2012b). Rain or meltwater enters bedrock joints and increases hydrostatic pressure. If the water freezes, incremental pressure wedges the rock away from the cliff face, leaving a slightly larger fracture when the ice thaws. Repeated freeze–thaw action may eventually destabilize the bedrock.

The freeze–thaw process likely triggered the November 1980 rockfall above the trail to Upper Yosemite Fall (Stock et al. 2012a). A 1,500-m^3 (53,000-ft^3) slab of rock broke loose, and the subsequent rockfall destroyed approximately 800 m (2,600 ft) of trail, killed three hikers, and injured another 19 visitors. Snowmelt and/or freeze–thaw processes may also have triggered the Ahwiyah Point rockfall in 2009 (Zimmer et al. 2012).

Ground-shaking from earthquakes may also trigger rockfalls (refer to the "Seismic Activity (Earthquakes)" section). Relatively few historic rockfalls in Yosemite National Park were generated by earthquakes, but these events are responsible for the greatest cumulative volume of rockfall material (Stock et al. 2012a). In 1872, a magnitude 7.6–8.0 earthquake in Owens Valley triggered abundant rockfalls throughout the southern Sierra Nevada. Three of six rockfalls recorded in the park contained estimated volumes exceeding 20,000 m^3 (710,000 ft^3) (Wieczorek and Snyder 2004). In 1980, earthquakes centered in the Mammoth Lake area triggered nine rockfalls and seriously injured two people in the park.

Most of the past rockfalls in Yosemite National Park were triggered by unrecognized or unreported mechanisms (Wieczorek et al. 1998). The triggering event for the 1987 Middle Brother rockfall, for example, remains unrecognized. Precise triggering mechanisms for the 1998 and 1999 rockfalls from Glacier Point could not be determined although rainfall and freezing temperatures may have contributed to a freeze–thaw triggering mechanism for the 1998 rockfall (Wieczorek and Snyder 1999).

Rockfall Inventory, Monitoring and Research

Talus piles have accumulated at the base of nearly every cliff in Yosemite Valley since the Tioga-aged glacier retreated from the valley about 15,000 years ago (Glazner and Stock 2010). Wieczorek and Snyder (2009) have provided a detailed methodology for monitoring potential slope movements by addressing five primary factors, or "vital signs": 1) landslide type, 2) landslide triggers and causes, 3) geologic materials involved in landslides, 4) instruments used to measure and assess landslide movement, and 5) landslide inventories and maps of historical landslide events. Methods used to monitor these vital signs range from basic to complex and as expected, require a range of expertise, time, and financial resources.

As Wieczorek and Snyder (2009) suggested, a landslide inventory map is essential for evaluating regional landslide hazards. In 1998, the U.S. Geological Survey identified and mapped two potential rockfall hazard zones in the Yosemite Valley: 1) a Talus Zone that included the talus piles at the base of cliffs or steep slopes, and 2) a "Rockfall Shadow" Zone that extended past the Talus Zone and into the valley (Wieczorek et al. 1998). However, the 2008 rockfall at Curry Village and the 2009 Ahwiyah Point rockfall (fig. 10) impacted areas that were not identified as at risk on the 1998 inventory maps, suggesting the need for a better understanding of rockfall hazards as well as improved mapping.

Since record keeping began in 1857, more than 900 rockfalls have been documented in Yosemite National Park. Most of these have occurred in Yosemite Valley (fig. 11; Stock et al. 2012a). A rockfall inventory for Yosemite National Park documents the location and relative size of 895 rockfalls that occurred between 1857 and early 2011 and lists the numbers of deaths and injuries related to these rockfalls; the damage to trails, roads, structures, or utilities; and the triggering mechanism, if known (Stock et al. 2012a). The inventory identifies areas in Yosemite Valley that are susceptible to rockfalls, rockslides, rock avalanches, and other types of landslides.

In 2003, Guzzetti et al. used a computer program to analyze potential rockfall hazards in Yosemite Valley (Guzzetti et al. 2003; Wieczorek and Snyder 2009). In 2010, the National Park Service realigned the rockfall hazard zone in Curry Village and closed all structures within the revised hazard zone (National Park Service 2010b). The quantitative assessment of rockfall risk in Yosemite Valley lead to the closure of additional structures in Curry Village in June 2012 (Stock et al. 2012a).

Rockfall monitoring and research is ongoing in Yosemite National Park. In 2008, the park partnered with Los Angeles–based xRez Studio to create the Yosemite Panoramic Imaging Project, which enables imagery-based rockfall monitoring in Yosemite Valley (National Park Service 2009b). The project created a 3.8-gigapixel photographic map of Yosemite Valley by combining gigapixel panoramic photography with LiDAR-based digital terrain modeling and 3-D computer rendering to capture Yosemite Valley in a single image. The image allows resource managers to examine the cliffs in detail without climbing them.

Gigapixel photography and airborne and terrestrial laser scanning data were used to evaluate the 2008 Curry Village rockfall detachment surface, adjacent cliff area, rockfall volume, and the geologic structure contributing to the rockfalls. The data revealed that failure occurred along an exfoliation (sheet) joint in the granodiorite (Stock et al. 2011).

Airborne and terrestrial LiDAR, high-resolution photography, and acoustic data were used to help analyze the initiation, dynamics, and talus deposition of the complex rockfall occurring at Ahwiyah Point on March 28, 2009 (Zimmer et al. 2012). Rock climbers who witnessed the event from across the valley recall the occurrence of a large rockfall during the night punctuated by several hours of smaller rockfalls. Then, at 5:26 a.m. (local time), a large block detached, slid off a ramp, fell approximately 350 m (1,100 ft) down the northwest face of Ahwiyah Point, and slammed into a ledge, dislodging additional rock material another 300 m (1,000 ft) down the cliff. The rockfall buried the southern portion of the Mirror Lake Loop Trail (fig. 10). When the rockfall struck the top of the talus slope, it generated an airblast that toppled hundreds of trees up to 50 m (160 ft) beyond the talus slope (Zimmer et al. 2012).

LiDAR data accurately determined the volume and dimensions of the detached block, the orientation of fractures bounding the block, the size and dip of the ramp, the vertical ballistic distance, the mid-cliff distance, and the volume of material dislodged from the mid-cliff impact. Seismic stations recorded two distinct detachment signals and a large impact signal. The impact of the rockfall remobilized talus, changing the talus slope angle and decreasing talus porosity, suggesting that talus slopes may preserve information about the size and dynamics of pre-historic rockfalls. Significantly, the use of these modern techniques allowed researchers to document nearly all of the important aspects of the Ahwiyah Point rockfall, including:

- The structural and geomorphic conditions that led to the failure,
- The precise timing and trajectory of the rockfall,
- The sequence of impacts and resulting volume changes, and
- The evolution of the talus slope due to high energy impact.

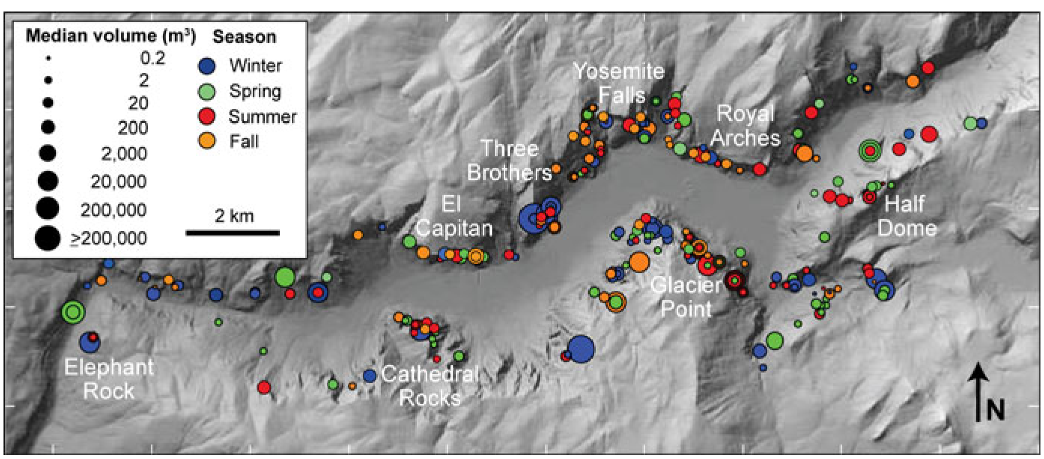


Figure 11. This map identifies rockfalls that have occurred in Yosemite Valley from 1857 to 2011. In 2011, 53 rockfalls were documented in the valley. These events had an accumulated volume of 2,200 m³ (78,000 ft³, or 6,000 tons). National Park Service map, available at http://www.nps.gov/yose/naturescience/rockfall.htm (accessed July 26, 2012).

Table 1. Significant observations and mechanical analysis of the August 2009 Rhombus Wall rockfall event.

Significant Observations	Conclusion
1. Each rockfall was a distinct event, separated in time from previous rockfalls by 20 seconds to 8 months.	Rockfalls were related through a time-dependent process of progressive failure along sheeting joints commonly bounded by regional discontinuities (moderately east-dipping surfaces in the cliff that formed the upper margins of failure surfaces).
2. In all rockfalls, thin sheets of rock failed along nearly planar fractures with similar orientations that roughly paralleled the pre-rockfall cliff surface.	
3. After the initial failure, all but one of the subsequent rockfalls either overlapped or occurred along the perimeter of at least one previous failure surface.	
4. Cracking sounds accompanied some rockfalls and in one case had visible sheeting joint opening.	
5. As the rockfall sequence progressed in time and space, the thickness of the failed sheets decreased.	
Mechanical Analysis	**Conclusion**
1. Cliff geometry dictates that tensile stresses should occur perpendicular to a steep, convex cliff face.	Progressive sequences of rockfalls that occur over a range of meteorological conditions do not need to be explained by a variety of triggering mechanisms. They may result from the time-dependent propagation of cracks due to stress redistribution following a previous rockfall.
2. Stress intensity factors indicate that sheeting joints should propagate parallel to a cliff face. High compressive stresses parallel to a cliff face allow a sheeting joint to propagate parallel to the cliff over distances many times the joint depth.	
3. Asymmetric stress concentrations at crack tips promote crack propagation and ultimately destabilize a cliff face, triggering rockfalls and setting the stage for further failures along the fracture periphery.	

Extracted from Stock et al. (2012b).

Laser scanning data, high-resolution photography, and video were also used in 2009 to document progressive sheet-joint type failure from the Rhombus Wall in Yosemite Valley. A series of rockfalls occurred on August 26, but propagation of the sheeting joints in the area continued for another 15 months, causing sporadic rockfalls. Analysis of the data helped define the origin, volume, debris pattern, and propagation of this 3-week rockfall event and provided important implications for rockfall hazard assessment (table 1; Stock et al. 2012b). Additional monitoring may be needed to evaluate the potential for additional, progressive rockfalls to occur up to weeks following the initial rockfall.

Recent studies of the 2009 Ahwiyah Point rockfall and the 2010 Rhombus Wall rockfall suggest that combining such tools as seismic, acoustic, LiDAR, and high-resolution photographic data offer valuable insights into the dynamics and associated hazards of rockfalls in Yosemite National Park and provide helpful information for future land-use planning. If alternative locations can be found, facilities currently in hazardous zones may be phased out or relocated. The exceptionally large boulders found scattered throughout Yosemite Valley indicate, however, that no area in the valley is absolutely safe from large rock avalanches (Wieczorek et al. 1998; Glazner and Stock 2010).

Rockslides west of the park boundary may also impact Yosemite National Park. In 2006, rock debris from the Ferguson rockslide closed a 180-m (600-ft) stretch of California Highway 140 leading into the park during peak tourist season. Failure occurred along an older landslide surface in weathered metamorphic rock and moved about 600,000 m^3 (21,200,000 ft^3) of material onto the highway. Future landslides of this volume may temporarily dam the Merced River. Since the 2006 landslide, the U.S. Geological Survey has installed a sophisticated monitoring system to detect future movement in the rockslide area (Glazner and Stock 2010).

Seismic Activity (Earthquakes)

Seismic activity surrounds the core of the Sierra Nevada (fig. 12). Strain and pressure continues to build up along the northwest–southeast-trending faults that form the eastern boundary of the Sierra Nevada and the western boundary of the Basin and Range Province. The sudden release of this strain causes earthquakes, and ground shaking from earthquakes triggers some, but not all, of the rockfalls in Yosemite National Park (Wieczorek and Snyder 2004).

Intense earthquake swarms centered southeast of Mammoth Lakes on May 25–27, 1980 triggered several thousand landslides throughout an area of approximately 2,500 km^2 (970 mi^2), including nine rockfalls in Yosemite National Park (Harp et al. 1984). Magnitudes ranged from 5.7 to 6.2 (California Geological Survey 2011). Rocks fell for thousands of feet, shattered on impact at the bases of cliffs, and generated rock avalanches that swept into the valleys. A rockfall in Half Dome Granodiorite (map unit Kdh) at Sierra Point critically injured two hikers (Wieczorek 1981). Along Sentinel Creek, earthquakes dislodged approximately 2,000 m^3 (71,000 ft^3) of primarily Sentinel Granodiorite (map unit Ks). Tremors from this earthquake swarm continued throughout the summer and may have been responsible for the collapse of three columns in Devils Postpile National Monument that had been leaning since 1909 (Harp et al. 1984; Graham 2009).

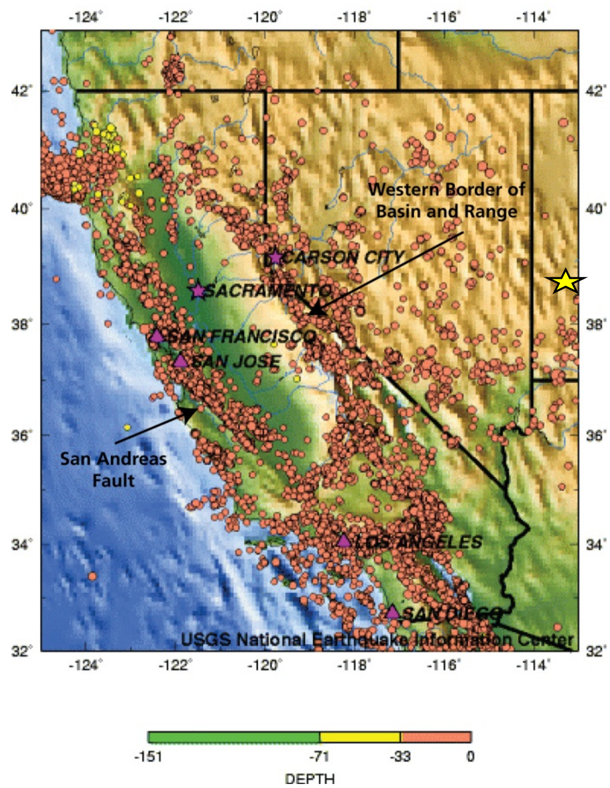


Figure 12. Seismicity in California from 1990 to 2006. Circles represent earthquakes, with color indicating depth (in kilometers) from the surface. The yellow star (not to scale) marks the approximate location of Yosemite National Park, purple triangles are cities, and purple stars are the capital cities. Note how seismic activity defines the boundaries of the Sierra Nevada. U.S. Geological Survey graphic, available at http://earthquake.usgs.gov/earthquakes/states/california/seismicity.php (accessed January 24, 2011). Annotations by the author.

The 1872 earthquake in Owens Valley killed 23 people and leveled most of the buildings in Lone Pine, California. More than 100,000 tons of Half Dome Granodiorite (map unit Khd) fell from the west face of Liberty Cap near Nevada Fall. The air blast from the rockfall moved a hotel at the base of Liberty Cap 5 cm (2 in) (Glazner and Stock 2010). Another large rockfall from Eagle Rock, near the present location of the Yosemite Valley Chapel, was vividly described by John Muir (Muir 1912).

Movement along the Owens Valley Fault may also have triggered the prehistoric El Capitan Meadow rock avalanche. This massive failure deposited approximately 2,190,000 m^3 (77,300,000 ft^3, roughly equivalent to 240,000 dump truck loads) of rock at the base of El Capitan. Sediment layers exposed in trenches dug across the fault indicate that movement along the fault occurred 3,300–3,800 years ago. To date the age of the El Capitan Meadow rock avalanche, geologists used the cosmogenic exposure dating technique developed in the 1990s, which measures the amount of the radioactive isotope, beryllium-10, that has accumulated on a rock's surface from exposure to cosmic rays. This dating suggests that the rock avalanche in El Capitan Meadow occurred about 3,600 years ago, which coincides with movement on the Owens Valley Fault (Glazner and Stock 2010; Stock and Uhrhammer 2010).

Earthquakes also pose a hazard to historic landmarks in the park. Potential earthquake damage to the Ahwahnee Hotel, a National Historic Landmark built in 1927, was one reason for the development of the park's Ahwahnee Comprehensive Rehabilitation Plan (National Park Service 2011b). When rehabilitation is completed, the hotel buildings and grounds will be in compliance with seismic standards, as well as current building and fire standards. As of December 2011, the park was reviewing public comments from fall 2010.

Like rockfalls, earthquakes are unpredictable. Both constitute potential hazards to visitor safety and infrastructure in Yosemite National Park. Monitoring of seismic data may help resource managers to determine the frequency of earthquake activity, evaluate earthquake risk, and interpret the geologic and tectonic activity of an area, and may provide an effective vehicle for public information and education (Braile 2009). Braile (2009) provided a summary of seismic monitoring methods, including the expertise, special equipment, financial resources, personnel, and labor intensity needed to implement each method.

Debris Flows, Flooding, and Erosion

Debris flows (sediment-rich slurries) and flood events modify river and stream channels, riparian habitat, and floodplains. Debris and high velocity floodwater may undercut cliffs; erode glacial moraines; and damage roads, sewer lines, and other infrastructure. For example, the 1997 Yosemite Valley flood caused $178 million worth of damage to roads, trails, buildings, campgrounds, utility systems, natural and cultural resources, and personal property (National Park Service 2007). In addition, natural widening of some sections of the Merced River has decreased riverbank stability and increased susceptibility to bank erosion during flood events. As global climate changes, the frequency of high-velocity, high-volume flooding in the Sierra Nevada is predicted to increase (see the Global Climate Change section).

Snowmelt in the High Sierra commonly causes seasonal flooding. However, exceptionally damaging winter floods typically occur following rain on snow events associated with the Pineapple Express, a winter weather pattern producing a channel of warm, moisture-laden air from the Western Pacific that dumps tremendous amounts of rain onto snow-bound peaks on the West Coast. Since 1916, warm winter rains falling on snow at elevations above 2,600 m (8,600 ft) have generated 11 winter floods that have caused extensive property damage (National Park Service 2004).

Large winter flood events in 1937, 1950, 1955, and 1964 generated discharge rates (the rate of flow during a moment in time) ranging from 240 to 280 m^3/s (8,400 to 9,860 ft^3/s), but the most severe flood event on record occurred in January 1997 (fig. 13). The Pineapple Express caused abundant precipitation in the Sierra Nevada in the fall of 1996. When 10 cm (4 in) of rain fell in Tuolumne Meadows on January 1, 1997, the snowpack was already about 180% of normal for the year, and both the ground and snowpack were saturated (Glazner and Stock 2010). Rain melted snow, and precipitation and snowmelt flowed down the forest floor.

A. Lower River Campground

B. Superintendent's Bridge

Figure 13. 1997 Merced River Flood. Floods erode river banks and deposit sediment and debris in floodplains. A. About 1 m (3 ft) of water inundated the entrance to Lower River Campground during the January 2, 1997 flood. Located in the Merced River floodplain, the Upper and Lower River campgrounds were closed permanently after the 1997 flood. B. The 1997 flood left this debris on the Superintendents Bridge. National Park Service photographs by Steve Thompson, courtesy of Yosemite Research Library.

At its peak, the Merced River has flowed 1.5 m (5 ft) above Pohono Bridge and discharged at a rate of 697 m^3/s (24,600 ft^3/s), significantly greater than normal discharge rates (Glazner and Stock 2010). For example, the greatest discharge in 2010 occurred on June 7 when the Merced River discharged at 199 m^3/s (7,010 ft^3/s) and rose 0.14 m (0.45 ft) above flood stage (10 ft) (US Geological Survey 2010). In the turbulent water of 1997, boulders would have moved like pebbles. Glazner and Stock (2010) helped to put such discharge in perspective by explaining that this volume of water "could have filled a sixty-thousand-seat football stadium in about eighteen minutes" (Glazner and Stock 2010, p. 114). For comparison, California Memorial Stadium on the University of California at Berkeley campus seats 71,799 people. The amounts of erosion and destruction to valley walls, riverbanks, and property within the floodplain were extensive. Damage to the local geologic features and park infrastructure by the debris and floodwaters included (National Park Service 2007):

- Undercutting of a rock slope below Highway 140 at Windy Point that resulted in the collapse of one lane (fig. 14),
- Washing out of 91 m (300 ft) of roadway at Cookie Cliffs,
- Damage to nine bridges in Yosemite Valley (fig. 13),
- Erosion of much of the park's 1,300-km (800-mi) trail system and destruction of 33 trail bridges,
- Destruction of a 91-m (300-ft) section of 36-cm (14-in) sewer line beneath Highway 140, and
- Flooding of 350 motel and cabin units at Yosemite Lodge and 200 concession employee quarters.

At Cookie Cliffs, the 1997 flood destroyed the same part of Highway 140 that had been destroyed in the 1982 rockslide (fig. 14). In this area, repeated rockslides had constricted the river's channel and diverted high water flow toward this section of road (Glazner and Stock 2010). Evidence from soils, tree growth, and archeological sites suggests that events like the 1997 flood are common in the Sierra Nevada, recurring on the order of decades to a few hundred years. However, evidence for larger floods is lacking, suggesting that floods larger than the 1997 flood have not occurred for thousands of years (Glazner and Stock 2010). Spring floods in 2011, for example, were similar to those of 2010, with floodwaters cresting at 3.2 m (10.43 ft) at Pohono Bridge and 2.5 m (8.03 ft) at the Happy Isles gage (National Park Service 2011c).

Debris Flow and Flooding Mitigation and Monitoring

Executive Order 11988, which applies to all federal agencies, requires the National Park Service to avoid locating any new facility in a floodplain unless no alternative location can be found. The location of class 1 facilities, such as administrative facilities, residential areas, warehouses, and maintenance buildings, are to avoid the 100-year floodplain; the location of class II facilities, which include medical facilities, emergency services, schools, depositories of irreplaceable records, museums, and fuel storage areas, are to avoid the 500-year floodplain. A 100-year flood describes an extreme flooding event that has a 1 in 100 (1%) chance of happening in any given year. While a 100-year flood may happen two years in a row, for example, the chances are slim that such an extreme event will take place with that frequency.

In Yosemite Valley, locating facilities away from the 100-year floodplain is complicated because of the complex Merced River floodplain. In meadow areas, for example, the floodplain is well developed, but in narrow canyons or where the river channel cuts into moraine deposits, such as in western Yosemite Valley, the floodplain narrows and flow velocities are high.

Seasonal flooding is further complicated by a dynamic March through April phenomenon called frazil ice that forms in Yosemite Creek (see Recent Geomorphic Features section). Frazil ice forms when air temperature suddenly drops below freezing, causing small ice crystals to develop in the turbulent super-cooled stream water (see the Features and Processes section). The ice crystals come together to form a thick slurry that may reach depths of 6 m (20 ft) along Yosemite Creek, covering the Lower Yosemite Fall Bridge (National Park Service 2004). Frazil ice does not have the erosional power of regular stream ice, but it can cause flooding. As frazil ice builds up and accumulates, it blocks Yosemite Creek and causes the stream to change direction. The full force of Yosemite Creek, which may be up to 3 m^3/s (100 ft^3/s), may divert towards foot bridges, roads, and buildings. At least one foot bridge has been destroyed and one displaced by frazil ice (National Park Service 2010c).

Frazil ice also poses a visitor safety issue. At first glance, frazil ice looks like snow, but it lies above the stream and obscures the actual stream depth. A visitor walking on frazil ice, assuming it was snow, might sink into water above his or her head (National Park Service 2010c).

As part of the Merced River's Wild and Scenic River Management Plan, new mapping will redefine the river's "ordinary high water mark," which is currently defined as "the 2.33 year flood or the level at which the river peaks every other year" (National Park Service 2011d). New 100- and 500-year floodplain maps for El Portal and Wawona will help locate any new development in these areas.

Stream channel morphology is influenced by complex interrelationships between regional geology, climate, topographic gradient, drainage basin history, river history, and sediment load. Lord et al. (2009) provided an overview of river and stream dynamics, described potential triggers of channel instability, and described methods to monitor streams and rivers. Monitoring the following characteristics, for example, can provide vital information about the condition and trends of both the Merced and Tuolumne Wild and Scenic River systems: 1) watershed landscape (vegetation, land use, surficial geology, slopes, and hydrology), 2) hydrology (frequency, magnitude, and duration of stream flow rates), 3) sediment transport (rates, modes, sources, and types of sediment), 4) channel cross- section, 5) channel planform, and 6) channel longitudinal profile (Lord et al. 2009).

Updated information about the Merced River Management Plan and the hydrology of Yosemite National Park, in general, may be obtained by contacting the Yosemite National Park hydrologist. Water quality data are also available from the National Park Service Water Resources Division, located in Fort Collins, Colorado.

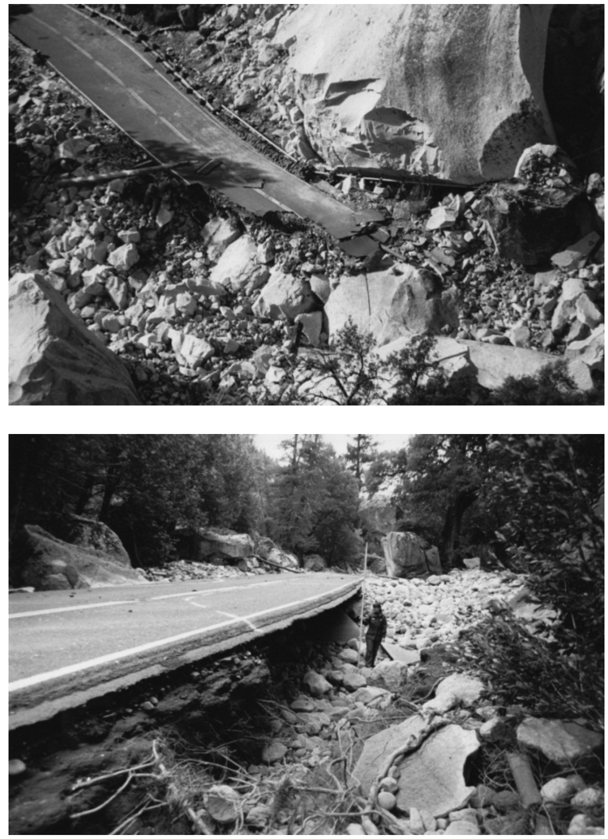


Figure 14. The 1997 flood destroyed this portion of California Highway 140 at the Cookie Cliffs rockslide. Top: Aerial view showing some of the extensive damage and the chaotic jumble of boulders. Bottom: Photograph showing the erosive power of the flood. Note the person for scale. The boulders are part of the Merced River's bed load, the material transported by the river's current. The 1997 floodwaters rearranged these boulders and transported them downstream. National Park Service photographs by Steve Thompson, courtesy of Yosemite Research Library.

Protection of Glacial Features

Yosemite National Park preserves evidence of glacial processes on a variety of scales. Many of the glacial features described in the Geologic Features and Processes section, such as U-shaped valleys, cirques, glacial moraines, and roches moutonnées, are massive landforms impacted by processes such as rockfalls, debris flows, earthquakes, and flooding. More subtle glacial features, such as glacial polish, striations, percussion marks, crescent gouges, chatter marks, and subglacial water polish are much more fragile and may be damaged or destroyed through natural weathering processes or vandalism.

Regardless of their size, glacial features provide important information about Pleistocene glacial history in Yosemite National Park and cannot be replaced. Glacial striations, crescent gouges, and chatter marks indicate the direction in which the glacier moved (fig. 15). Glacial polish on Marmot Dome is the only evidence that it was once covered by glacial ice (fig. 16). In addition, repeat photographs of granitic domes in the Tuolumne Meadows area show that many glacial erratics once perched precariously on the domes have been trundled, or pushed off, by visitors (Greg Stock, Geologist and Resource Manager, Yosemite National Park, written communication, April 4, 2012).

Natural weathering processes have eroded away some of these features, but the shiny, polished surfaces also attract visitors. The extent of human impacts on these glacial features is not well understood.

Various publications (e.g., Huber 1989; Glazner and Stock 2010) contain photographs that document examples of these glacial features. Photographs of these features may also be compiled from the Yosemite Research Library. Mapping specific glacial sites and documenting the glacial features with photographs and written descriptions could also help preserve this part of the park's glacial story for future generations. Such a project may be suitable for the NPS Geoscientists-in-the-Parks Program. The NPS Geologic Resources Division may be contacted for more information.

Reclamation of Abandoned Mines

Following the 1848 discovery of gold in the Sierra Nevada, mining settlements and activities contributed much to the colorful human history of this region. Within Yosemite National Park, 62 documented abandoned mineral land (AML) features are present at 20 sites (NPS Geologic Resources Division AML database, accessed December 20, 2011). Abandoned mine reclamation is actively being addressed in the park.

Prospectors explored Mono Pass for gold and silver as early as 1860. Miners established other high-altitude mines near the present eastern border of the park, such as the Bennettville and Great Sierra mines, near Tioga Pass to the north. In 1879, the Golden Crown Mine was drilled into metamorphic rocks (map unit PPNhcl) at 3,400 m (11,000 ft) on Mono Pass. Five log cabins remain from the bustling mining activity at the Golden Crown Mine and nearby Ella Bloss Mine. Because this mine complex remains surprisingly intact, it has been nominated to the National Register of Historic Places and will not be reclaimed (National Park Service 2008b).

The especially large and potentially hazardous Barite Mine, west of the park near El Portal, California, opened in 1927, targeting layers of barite in the Cretaceous Bass Lake Tonalite (map unit Kblt). The barite was used

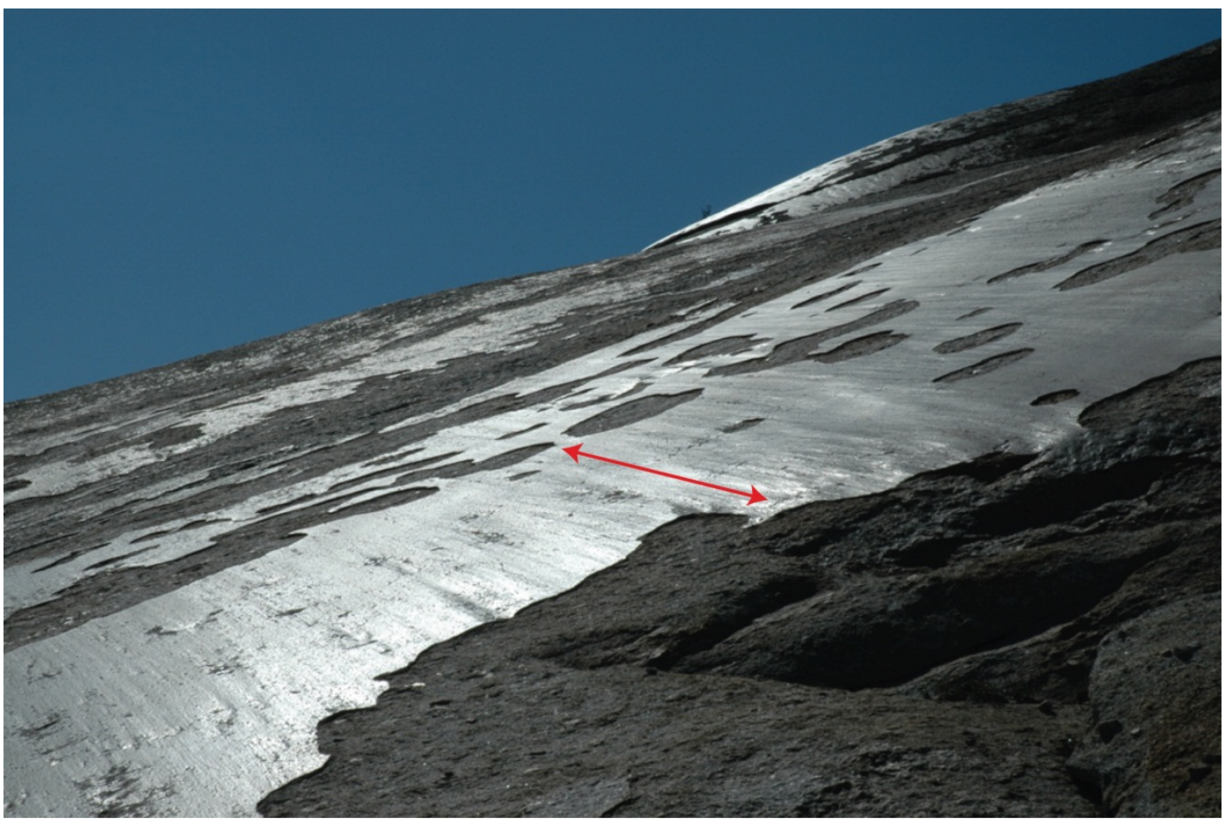


Figure 15. Striations (red arrow) on the glacial polish of Stately Pleasure Dome above Tenaya Lake. The surface became polished when debris transported by glacial ice scraped across the bedrock and scratched lines (striations) in the granodiorite. These striations indicate the direction of ice flow. As the polished surface layer flakes off, evidence of glaciation also disappears. National Park Service photograph courtesy of Greg Stock (Yosemite NP). Annotation by the author.

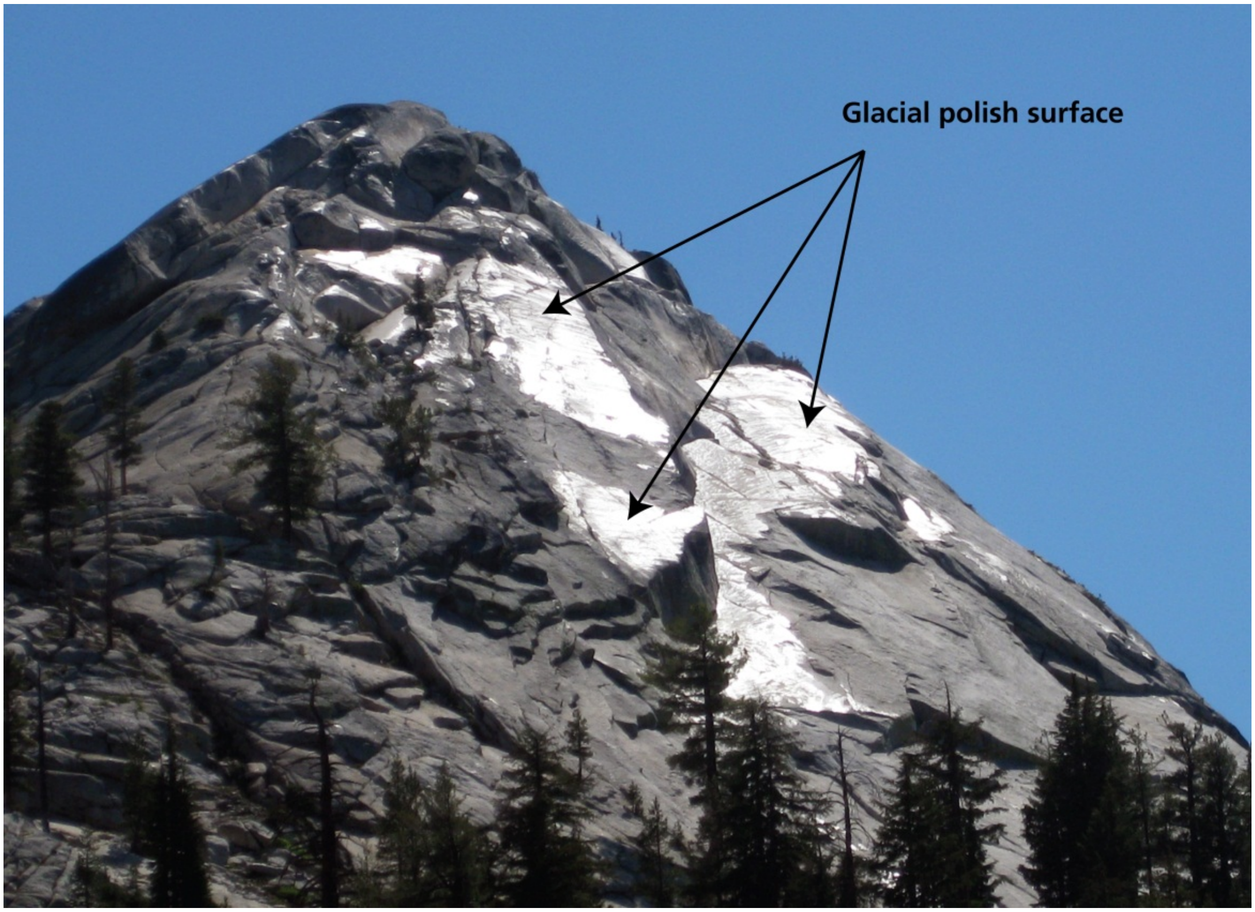


Figure 16. Glacial polish (arrow) forms the shiny surface in this photograph of Marmot Dome, located south of Tuolumne Meadows. The polished surface indicates that glacial ice once covered the dome and polished the Cathedral Peak Granodiorite (map unit Kcp) that forms it. Weathering and erosion have eliminated all but this remaining patch of glacial polish, which will eventually be removed by natural processes. National Park Service photograph courtesy of Greg Stock (Yosemite NP). Annotation by the author.

primarily in oil-well drilling. In 2010, an extensive project was completed to mitigate potential hazards at the mine (Greg Stock, Geologist and Resource Manager, Yosemite National Park, e-mail communication, January 20, 2011).

Additional information regarding mine reclamation at Yosemite National Park may be obtained from Dr. Greg Stock (park geologist) or from the NPS Geologic Resources Division in Lakewood, Colorado.

Global Climate Change

Climate change is a global issue that is affecting, and will continue to impact, the natural resources and infrastructure of Yosemite National Park. In general, the western United States is predicted to become drier. However, precipitation in the Sierra Nevada is projected to increase, although the percentage of precipitation falling as snow will decrease (Karl et al. 2009). The type and timing of precipitation will influence California's water budget and may play a role in future decisions regarding the restoration of Hetch Hetchy Canyon.

The frequency of intense rainfall events will likely increase in the Sierra Nevada, which may lead to increased flooding (Karl et al. 2009). If projections are accurate and warming raises the snow line (the elevation at which snow changes to rain) by a few thousand feet, most of the area in Yosemite National Park that now receives snow will receive rain, and events like the 1997 flood may become more frequent (Glazner and Stock 2010).

In addition to being critical to the park's ecosystems, the snowpack in the Sierra Nevada provides water as it melts in warmer, drier months. Increased warming is predicted to shift surface runoff and snow melt to earlier in the spring, resulting in the availability of less water in late summer (Karl et al. 2009). As Lundquist and Roche (2009) pointed out, "earlier snowmelt and a greater proportion of rain result in more water flowing into rivers in winter when it is a hazard, and less into rivers in summer when it is a resource" (Lundquist and Roche 2009, p. 1). To track changes in California's freshwater supply, the NPS Sierra Nevada Network monitors and analyzes the Sierra's snowpack, snow melt, lake outflow, stream flow, and wetlands hydrology (NPS Climate Change Response Program 2010).

The glaciers in the Sierra Nevada tie directly to the water budget and are principal indicators of climate change. They are important to alpine hydrology and global sea-level rise. Sierra Nevada glaciers have lost an average of

50% of their surface area since the Little Ice Age that began about 1350 C.E. (Common Era, preferred to "A.D.") and ended about 1850 C.E. (Glazner and Stock 2010). Shrinking glaciers result in earlier spring runoff, drier summer conditions, and less water entering streams after the seasonal snowpack has melted (Basagic and Fountain 2011). A warmer North American climate may eventually eliminate all glaciers in the Sierra Nevada.

The most comprehensive inventory of glaciers in the American West, compiled using 1:24,000 topographic maps, documents 1,523 glaciers ranging in size from 0.001 km^2 (0.0004 mi^2) to 31.62 km^2 (12.21 mi^2) (Fountain et al. 2007). Most of the glaciers are small, with 39.5% covering 0.01 km^2 (0.004 mi^2) or less. Various methods have yielded different counts of modern glaciers in the Sierra Nevada. A U.S. Geological Survey glacier photography flight in 1972 recorded 497 glaciers at least 0.01 km^2 (0.004 mi^2) in size in the Sierra Nevada (Raub et al. 2006). In 2010, Glazner and Stock (2010) reported about 100 small glaciers occupying north- and east-facing cirques in the higher elevations of the Sierra Nevada. Using 1:24,000 topographic maps, Basagic and Fountain (2011) mapped 1,719 alpine glaciers in the central and southern Sierra Nevada, of which only an estimated 122 were considered to be "true" glaciers containing moving ice.

Glaciers are dynamic natural resources. Whether they grow or recede depends directly on long-term temperature and precipitation trends, rather than on short-term, annual changes in precipitation or melting rates. Thus, glaciers are valuable indicators of long-term climate change. Glaciers influence local, regional, and even global ecosystems. In Yosemite National Park, high-altitude meadows, such as Tuolumne Meadows, depend on glacial meltwater. Water tables will lower as glaciers disappear, affecting meadow habitats and reducing late-summer water supplies. Perennial rivers may become ephemeral streams, and ephemeral streams that currently feed some waterfalls, such as Yosemite Falls, may become drier earlier in the summer (Lundquist and Roche 2009).

Modern glaciers in Yosemite National Park are melting rapidly. Gone from Merced Peak is the modern glacier discovered by Muir in 1871. In the last 100 years, significant melting has dramatically reduced the size of the Lyell, Dana, Maclure, Dragtooth, and Conness glaciers (fig. 17, table 2; Basagic and Fountain 2011). Although mapped as a single continuous glacier in 1883, the Lyell Glacier, considered to be the second largest in the Sierra Nevada, now consists of two lobes separated by an exposed ridge (Huber 1989). In 2004, the surface of the larger West Lyell lobe covered approximately 0.28 km^2 (0.12 mi^2) and the East Lyell lobe covered about 0.14 km^2 (0.05 mi^2) representing reductions of 40% and 78%, respectively, since 1903 (table 2; Basagic and Fountain 2011). With continued global warming, the Lyell Glacier is projected to disappear in a few decades (Greg Stock, Geologist and Resource Manager, Yosemite National Park, quoted in Bumgardner 2010).

These shrinkage rates are similar to those of other glacier-covered areas globally. For example, the Southern Alps in New Zealand lost 49% of glacier area between 1850 and 2006, and the European Alps lost 35%. In the Lewis Range of Glacier National Park, glacier area decreased by 65% from 1850 to 1979. Glaciers in Mount Rainier National Park shrank 19% between 1910 and 1994, and other glaciers in the Pacific Northwest, such as Mount Hood (34% loss) and Mount Adams (49% loss), experienced comparable melting. From 1909 to 2004, glaciers in the Colorado Front Range decreased by 40%.

Table 2. Reduction in the areas of glaciers on the eastern border of Yosemite National Park, 1903–2004.

Glacier	Change in Area (%)
Dragtooth	–74
Conness	–52
Dana	–64
Maclure	–47
West Lyell	–40
East Lyell	–78

Source: Basagic and Fountain (2011)

At current melting rates, most glaciers in the Sierra Nevada will be gone in 50 to 125 years (Basagic and Fountain 2011). The loss of these frozen reservoirs of fresh water will reduce streamflow during summer droughts and result in increased stream water temperatures. Changes in stream volume and temperature will impact instream flora and fauna, perhaps reducing the number of current cold-water organisms and increasing the species of warm-temperature biota (Basagic and Fountain 2011).

Monitoring glacial response in Yosemite National Park to global climate change may help park staff to predict and manage changes in the hydrologic and ecologic systems that depend on glaciers. To identify trends in glacial change, Karpilo (2009) described procedures to monitor four primary characteristics of a glacier: 1) annual glacier mass balance, 2) glacier terminus position, 3) glacier area, and 4) glacier surface velocity. Currently, Yosemite National Park is monitoring these characteristics in a 4-year project in collaboration with Bob Anderson of the University of Colorado, Boulder (Greg Stock, Geologist and Resource Manager, Yosemite National Park, written communication, April 4, 2012).

Preservation of the Geologic Landscape

Yosemite National Park was established to preserve its unique geologic resources, which include the greatest concentration of granite domes in the world, one of North America's highest measured waterfalls (Yosemite Falls), and some of the largest exposed granite monoliths in the world. Compared to the wilderness and range land experienced by John Muir, today's Yosemite has a wide variety of infrastructure, nearly all of which is located in Yosemite Valley: 344 km (214 mi) of paved roads, 109 km (68 mi) of graded roads, 32 km (20 mi) of paved walks and bicycle paths, and 1,287 km (800 mi) of trails. In addition to several lodges, visitors can choose among 1,504 campground sites. Nearly 4 million visitors travelled to Yosemite National Park in 2011 to experience the geologic wonders of the park. Resource managers face the major challenge of preserving the geologic landscape of the park for visitors while simultaneously preserving the landscape from such high levels of visitation.

The park's Scenic Vista Management Plan (National Park Service 2011e) addresses the preservation of the breathtaking scenery that inspired the federal government to grant Yosemite Valley to the state of California as a park in 1864. Over time, some of the geologic features responsible for this scenery have become obscured by vegetation. Implementation of the Scenic Vista Management Plan began in the fall of 2011. Under the plan, thousands of trees will be removed to reestablish and maintain the important historic views in Yosemite, including El Capitan, Half Dome, mountain meadows, and the park's numerous waterfalls.

Rock climbers are literally connected to the geologic landscape of the park. Yosemite is one of the world's great rock-climbing destinations. Most climbs and cliffs in the park are in designated wilderness areas. A variety of impacts are associated with rock climbing: soil compaction, erosion, and vegetation loss in parking areas, at the bases of climbs, and on approach and descent trails; destruction of cliff-side vegetation and lichen; disturbance of cliff-dwelling animals; litter; water pollution from improper human waste disposal; and the visual blight of chalk marks, pin scars, bolts (which can only be installed with hand-powered drills), rappel slings, and fixed ropes (National Park Service 2011f). Responsible climbers and practices minimize these impacts. Additional information about rock climbing can be found on the park's website (http://www.nps.gov/yose/planyourvisit/climbing.htm).

Currently, land managers are using social science methods to integrate and better understand visitor characteristics and behavior with natural resources (National Park Service 2011g). The Visitor Use and Social Science branch of the Resources Management and Science division conducts research on visitor use patterns and behavior to help resource managers make land-use decisions.

As of January 2012, several other projects with geologic landscape components are either underway or proposed for Yosemite National Park, including: Merced and Tuolumne Wild and Scenic Rivers management plans, Curry Village Rockfall Hazard Zone Structures Project, Half Dome Trail stewardship plan, Tioga Road rehabilitation plan, Ahwahnee Comprehensive Rehabilitation Plan, and the Tenaya Lake Area Plan. These plans are available online: http://www.nps.gov/yose/parkmgmt/planning.htm (accessed January 9, 2012).

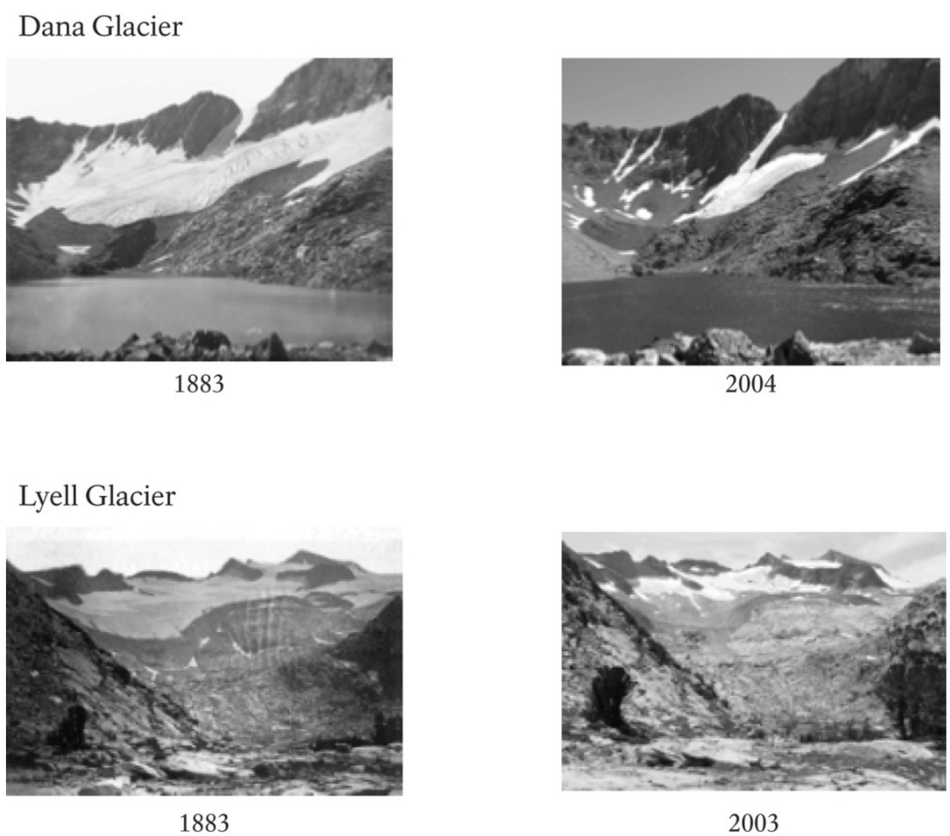


Figure 17. Photographic evidence of modern glacial melt in Yosemite National Park. Basagic (in Basagic and Fountain 2006) used historical US Geological Survey photographs by I.C. Russell (A, C) and re-photographed the Dana (B) and Lyell (D) glaciers from the same locations. The photographs serve as visual evidence of glacial change over time. Photographs courtesy of the Glacier Research staff at Portland State University, available at http://www.glaciers.pdx.edu (accessed January 16, 2012).

Geologic Features and Processes

Geologic resources underlie park ecosystems and geologic processes shape the landscape of every park. This section describes the most prominent and distinctive geologic features and processes in Yosemite National Park.

Yosemite National Park contains far too many individual geologic features to describe each one in detail within the scope of this geologic inventory. Thus, this section offers an overview of the geologic features and processes found within the park, grouped into 11 general categories:

- Granitic bedrock
- Diorite of the Rockslides
- Metamorphic bedrock
- Volcanic bedrock
- Rockfalls, rockslides, and talus piles
- Rock climbing related features
- Joints
- Pleistocene glacial features
- Modern glacial features
- Waterfalls
- Recent geomorphic features.

Granitic Bedrock

Most plutonic rocks in the Sierra Nevada Batholith consist of five readily recognizable minerals: quartz, potassium feldspar (orthoclase), plagioclase feldspar, biotite, and hornblende (fig. 18). Quartz is typically clear, although it may be white or smoky, and is harder than the other minerals. Quartz crystals in granitic rocks are generally blob-like, lacking well-defined borders. Orthoclase is white or pink, and plagioclase is white or gray. Unlike quartz, both feldspars cleave along distinct and nearly perpendicular surfaces, so at least one squared- edge of a feldspar crystal can be recognized in a granitic rock. Opaque, black biotite has a shiny luster and breaks along only one plane of weakness, which allows it to flake into thin sheets. Like biotite, hornblende contains magnesium and iron, which gives it a greenish-black color. Unlike biotite, hornblende crystals have a dull luster and form thin, rectangular shapes on the surface of a rock.

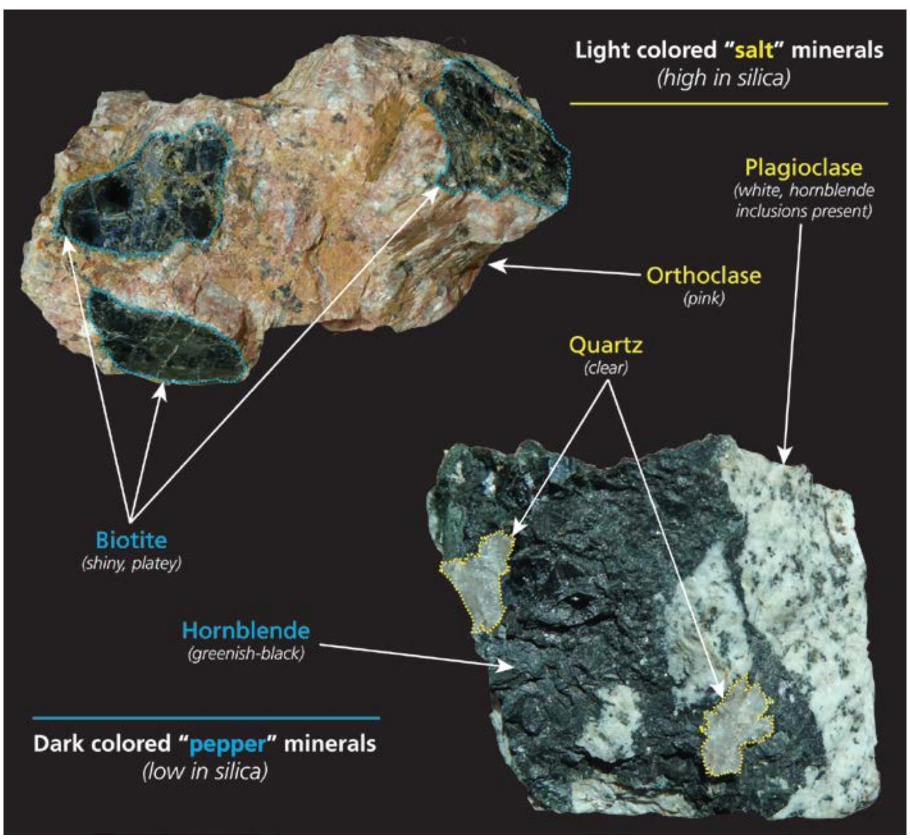


Figure 18. Major mineral components of plutonic rocks. Plutonic rocks consist primarily of five readily recognizable minerals in varying proportions. These rocks are classified based on the relative proportions of quartz, potassium feldspar, and plagioclase (see fig. 6). Graphic by Rebecca Port (Colorado State University).

The names of the common plutonic rocks are based on the relative proportions of quartz, potassium feldspar, and plagioclase. Most rocks in Yosemite National Park contain primarily quartz and plagioclase and fall in the granitic rock classification of granite, granodiorite, and tonalite (fig. 6). Biotite and hornblende tend to be more abundant in plutonic rocks that contain more plagioclase than potassium feldspar. As a result, these minerals impart a dark, speckled appearance to granodiorite. Tonalite is even darker than granodiorite. These granitic rocks are often described as having a "salt-and-pepper" appearance due to the relative abundance of light and dark minerals. Granitic rocks in the Sierra Nevada commonly contain potassium feldspar phenocrysts up to 5–8 cm (2–3 in) in length that impart a porphyritic texture (Huber 1989).

Geologists use mineral composition, texture, age of the rock, field relationships, and other techniques to distinguish individual plutons. In Yosemite National Park, granitic rocks have been named using a representative geographic feature and the composition of the rock, such as El Capitan Granite (map unit Kec), Half Dome Granodiorite (map unit Khd), and the Granodiorite of Kuna Crest (map unit Kkc). Determining the origin of granitic boulders in Yosemite National Park is also useful for tracking glacier movement (see Glacial Features).

Intrusive suites, such as the Tuolumne Intrusive Suite, represent plutonic units of a similar age that may share a common parent magma (Huber 1989; Glazner and Stock 2010). For example, the Tuolumne Intrusive Suite, which was emplaced between 97 and 85 million years ago, underlies most of Yosemite National Park (Glazner and Stock 2010). Ten intrusive suites have been mapped on the accompanying GIS map of Yosemite National Park (fig. 5; Huber et al. 1989). The units of each intrusive suite are also identified and described in the Map Unit Properties Table and the Geologic Map Overview Graphics (in pocket).

The granitic rocks in Yosemite National Park are primarily Cretaceous in age. Older, Jurassic plutonic rocks occur west of the Big Oak Flat entrance, and some Triassic plutonic rocks are exposed east of the park in Lee Vining and Lundy canyons. Examples of the various rock types are displayed at the Valley Visitor Center and are exposed in Yosemite Valley and the Tuolumne Meadows area, which are easily accessible to visitors.

As described in the Rock Climbing Related Features section, characteristics of the granitic rocks, including their mineral composition and weathering and erosion patterns, have created ideal locations for rock climbing, a sport commonly practiced in Yosemite National Park and throughout the Sierra Nevada.

Granitic Rocks of Yosemite Valley

Granodiorite of Arch Rock (map unit Kar) and Tonalite of the Gateway (not mapped within the extent of the GRI GIS data) form the walls of Merced Gorge and the west end of Yosemite Valley and are among the oldest plutonic rocks in the valley (Huber 1989). The El Portal Road (the extension of California Highway 140 within the park) passes under two large fallen blocks of Arch Rock Granodiorite just east of the Arch Rock Entrance Station. Gateway Tonalite, which has a radiometric age of approximately 114 million years, is exposed east of El Portal where the road begins to climb up Merced Gorge (Huber 1989).

These older plutonic rocks were intruded by the El Capitan Granite (map unit Kec) about 108 million years ago (Huber 1989). Along most of its margins, the lighter El Capitan Granite mingles with the Diorite of the Rockslides (see next paragraph). Turtleback Dome, El Capitan, Three Brothers, and Cathedral Rocks are hewn from El Capitan Granite. The 1982 Cookie Cliff landslide left white boulders of El Capitan Granite along the El Portal Road about 4 km (2.5 mi) east of the Arch Rock Entrance Station.

El Capitan Granite contains abundant quartz, plagioclase, orthoclase, and biotite, but little hornblende (fig. 19). It is characterized by relatively large [up to 1.3 cm (0.5 in) long] orthoclase crystals and fist-sized, dark gray blobs of biotite-rich (dark) diorite called enclaves (French for "enclosed"). The enclaves may represent basaltic magma that mixed with the granitic magma, broke apart, and became dispersed throughout the lighter granite (Glazner and Stock 2010). Common in western Yosemite Valley, the diorite enclaves may have originated from the magma that crystallized into the Diorite of the Rockslides, which forms the talus slopes west of El Capitan.

Figure 19. El Capitan Granite. The granite's "salt-and-pepper" appearance results from the relatively equal distribution of light-colored minerals (quartz, potassium feldspar, and plagioclase) and dark-colored minerals (primarily biotite). The dark blob in the center is an enclave of diorite. Penny for scale. National Park Service photograph courtesy of Greg Stock (Yosemite NP).

Taft Granite (map unit Ktg) intruded El Capitan Granite and forms the brow of El Capitan. It is also present in part of the upland between El Capitan and Fireplace Bluffs, at Dewey Point, and near The Fissures, east of Taft Point. Although similar in appearance to El Capitan Granite, Taft Granite is lighter in color, commonly finer grained, and lacks phenocrysts.

Rounded clots of dark minerals give the Leaning Tower Granite (map unit Klt) a spotted appearance, whereas evenly distributed light and dark minerals give the Bridalveil Granodiorite (map unit Kbv) a salt-and-pepper appearance. The Bridalveil Granodiorite has intruded nearly all of the rocks it now contacts, indicating that it is younger than the surrounding plutonic rocks.

A north–south band of gray Sentinel Granodiorite (map unit Ks) crosses Yosemite Valley between Taft Point and Glacier Point (Huber 1989; Huber et al. 1989). The medium-grained granodiorite contains massive inclusions of El Capitan Granite, which are exposed on the face of the cliff near Yosemite Falls. In a roadcut near the trailhead to Taft Point, dikes (narrow, tabular intrusions of igneous rock) of Sentinel Granodiorite cut inclusions of El Capitan Granite, indicating that the Sentinel Granodiorite is younger.

Plutonic rocks at Glacier and Washburn points that were once thought to be part of the Sentinel Granodiorite are now known as the Granodiorite of Kuna Crest (map unit Kkc). Parallel-oriented biotite flakes and hornblende rods give the granodiorite a streaky appearance.

Except for a few intrusive dikes (map unit Kapp), the medium- to coarse-grained Half Dome Granodiorite (map unit Khd) is the youngest plutonic rock in the Yosemite Valley area (fig. 6). Emplaced approximately 87 million years ago, Half Dome Granodiorite is mapped in Yosemite Valley east of Curry Village. In addition to underlying its namesake, Half Dome, it also forms the sheer cliffs north of the trail between the Ahwahnee Hotel and Mirror Lake. Rockfalls near Mirror Lake expose fresh blocks of this granodiorite. Good exposures of Half Dome Granodiorite are also found at Olmsted Point and along the trail to Vernal and Nevada falls.

Half Dome Granodiorite contains relatively large crystals of hornblende, biotite, both feldspars, and sphene. Well-formed rectangular hornblende crystals that may exceed 1.3 cm (0.5 in) in length are characteristic of this granodiorite. Like flipping pages in a book, shiny flakes of biotite can be peeled away easily from thick, hexagonal biotite crystals roughly 0.64 cm (0.25 in) wide. The honey-colored, diamond-shaped sphene crystals may be as large as the biotite (Glazner and Stock 2010), and quartz fills the intervening spaces.

Granitic Rocks of the Tuolumne Meadows Area

Half Dome Granodiorite and the Granodiorite of Kuna Crest (map unit Kkc) form the eastern end of Yosemite Valley and the western margin of the Tuolumne Intrusive Suite (Huber et al. 1989). Granitic rocks in the Tuolumne Intrusive Suite (fig. 5), which is well- exposed in Tuolumne Meadows and along the Tioga Road, represent four episodes of magma emplacement. From oldest to youngest, the sequence includes: 1) Granodiorite of Kuna Crest (about 91 million years old), 2) Half Dome Granodiorite, 3) Cathedral Peak Granodiorite (map unit Kcp; about 86 million years old), and 4) Johnson Granite Porphyry (map unit Kjp; Huber 1989).

The Granodiorite of Kuna Crest represents the initial intrusion and solidification of granitic magma in the Tuolumne Meadows area. Crystals in this granodiorite are smaller and more uniform in size than those in some other granitic rocks in Yosemite National Park, such as the El Capitan Granite. Dark minerals (primarily biotite and hornblende) are also more abundant. Because biotite and hornblende crystallize at higher temperatures than quartz and feldspar as magma cools, the Granodiorite of Kuna Crest is not only the oldest granitic rock in the Tuolumne Intrusive Suite but also the darkest in color. Blasting to build the parking area at Glacier Point has exposed this granodiorite at the base of the stairs connecting the lower and upper parking areas.

Following the emplacement of the Granodiorite of Kuna Crest, surges of fresh magma injected both the equigranular and porphyritic phases of Half Dome Granodiorite into the Kuna Crest pluton (Huber 1989). In the Tuolumne Meadows area, exposures of Half Dome Granodiorite may be found adjacent to the turnout at Olmstead Point, west of Tenaya Lake.

A third surge of magma solidified into Cathedral Peak Granodiorite (map unit Kcp). Roadcuts near Pywiack Dome expose this granodiorite, which underlies nearly all of the area along Tioga Road between Tenaya Lake and Tioga Pass (Glazner and Stock 2010). Although both Half Dome and Cathedral Peak granodiorites consist of about 25% orthoclase crystals, the crystals in Cathedral Peak Granodiorite are much more distinctive and are typically 8–10 cm (3–4 in) long (fig. 6). Huge crystals such as these, known as megacrysts, indicate that the magma body cooled very slowly over millions of years.

In the Tuolumne Meadows and Tenaya Lake area, many dikes of white, fine-grained rock known as aplite cut the granitic rocks (fig. 6). Aplite forms after about 90% of the initial magma has solidified. The remaining 10% of liquid magma is very fluid and fills cracks in the surrounding rock. Quartz and feldspars are the principal minerals in aplite dikes. In some areas, the last liquid magma crystallized into pegmatite, a rock composed of very large crystals [0.3 m (1 ft) or more in width] (Glazner and Stock 2010). Aplite dikes and pegmatites are distinguished on the basis of texture, rather than composition.

The final intrusion of magma in the Tuolumne Intrusive Suite produced the light-colored Johnson Granite Porphyry (map unit Kjp), which contains conspicuously large crystals set in a fine-grained groundmass (fig. 6). Intruded into the Cathedral Peak Granodiorite, the Johnson Granite Porphyry has, in turn, been cut by younger aplite dikes.

The porphyry contains textures ranging from aplite to pegmatite, phenocrysts and megacrysts of orthoclase, and rounded, reddish blobs of Cathedral Peak Granodiorite. This textural variety in the Johnson Granite Porphyry suggests a possible association with an explosive volcanic event. However, erosion has removed any volcanic rocks that may have been associated with the igneous intrusion. The diverse textures of the Johnson Granite Porphyry are exposed on the trail from the Tuolumne Meadows Campground to Elizabeth Lake (Glazner and Stock 2010).

Diorite of the Rockslides

Diorite contains mostly plagioclase and dark minerals with little quartz and orthoclase (fig. 6). The Rockslides, west of El Capitan, offer excellent exposures of diorite (map unit KJqdg). Broken blocks of diorite are visible in the talus slopes below the Rockslides and along the old Big Oak Flat Road (Glazner and Stock 2010).

Metamorphic Bedrock and Terranes

Two northwest-trending belts of metamorphic rocks border the park to the west and east. Most of the original fine-grained sediments that would eventually be metamorphosed were deposited between 600 and 150 million years ago in deep marine environments that would eventually become central California. Subduction along the western margin of North America and subsequent emplacement of the molten material that now forms the granitic bedrock of Yosemite National Park deformed and metamorphosed these sediments (see the Geologic History section).

The metamorphic rocks bordering the Sierra Nevada and the granitic plutons that formed the Sierra Nevada Batholith, document a subduction complex that existed along the western margin of North America throughout the Mesozoic. The complicated magma chamber fueled Cascade-like volcanoes in the Sierra Nevada, although erosion has removed much of the evidence of this past volcanic activity. Subduction processes continue to the north in the Cascade Range and to the south in Central and South America, but the growth of the San Andreas Fault system in the Cenozoic shut off the subduction complex along much of today's California coast. Cenozoic uplift and erosion processes have exposed metamorphosed rocks and hardened magma that originally developed far underground.

Western Metamorphic Belt

In the western metamorphic belt, the Mesozoic emplacement of the Sierra Nevada Batholith metamorphosed and intensely deformed older Triassic and Paleozoic sandstones, siltstones, conglomerates, shale, limestone, and chert. Most of these units lay west of the park boundaries in northwest-trending terranes, assemblages of rocks that share a common geologic history and are separated from other assemblages by faults (Bateman 1992). Much of California consists of accreted terranes, large assemblages of rocks that originally formed elsewhere, were subsequently transported by plate tectonic processes, and ultimately collided with and accreted onto western North America. The folding, faulting, and depositional history of these terranes is extremely complex and beyond the scope of this report. Only a brief overview is presented here.

Metamorphosed volcanic and sedimentary rocks of the Mesozoic-aged Mariposa Formation border the sedimentary fill of the Central Valley and form the westernmost rocks in the western metamorphic belt. The fine-grained mudstone and siltstone of the Mariposa Formation has been metamorphosed into slate and schist. The layers have been deformed and tipped nearly vertical to form the characteristic "tombstone rocks" of the Sierra Nevada foothills (Glazner and Stock 2010). Gold veins in the Mariposa Formation sparked the 1849 gold rush in California.

The Melones Fault Zone separates the Mariposa Formation from the Sullivan Creek Terrane. The terrane consists of dark, metamorphosed, serpentine-rich rocks (greenstones) from Earth's mantle and metamorphosed volcanic rocks that represent an island-arc assemblage. An island arc (also called a volcanic arc) is a linear, often curved, zone of volcanic islands that form above a subduction zone, similar to the Japanese islands in the western Pacific. Serpentine, a group of green, waxy- or greasy-appearing, magnesium-rich minerals, is the primary mineral type in serpentinite, California's state rock. Some greenstones are elongate blobs of hardened, pillow-shaped lava that formed when lava erupted underwater and rapidly cooled, causing new magma to break through the crust.

The Calaveras Complex, which lies east of the Sullivan Creek Terrane, consists of layered, sedimentary rocks that were deposited in a subduction zone; metamorphosed to black and green slate, schist, and greenstone; then severely deformed by collision with the western margin of the ancestral North American Plate, possible movement along the Sonora Fault Zone, and intrusion by the Sierra Nevada Batholith (see the Geologic History section).

The oceanic rocks of the Paleozoic Shoo Fly Complex, which intersects the southwestern corner of the park (map units PZpsq, PZps, and PZpr), have been compressed, metamorphosed to quartzite and schist, displaced by numerous faults, intruded by Sierra Nevada plutons, uplifted, and eroded. The units have lost their original bedding characteristics. Massive, light-colored outcrops of quartzite contrast with darker biotite schist (Peck 2002).

Eastern Metamorphic Belt

Metamorphosed volcanic rocks and sedimentary rocks are exposed along the eastern border of Yosemite National Park (Bateman et al. 1983; Huber et al. 1989). Paleozoic sandstone, conglomerate, and limestone have been metamorphosed to quartzite, metaconglomerate, and marble, but the most common metamorphic rock is hornfels. Hornfels is a general term for a fine-grained rock typically formed by contact metamorphism by an intrusion of molten material. In the GRI digital geologic (GIS) data, the hornfels, marble, and quartzite exposed in the Virginia Peak area (northeastern corner of the park) have been mapped as Paleozoic units (map units PPNhtp, PPNqz), but they are of uncertain age. Huber et al. (1989) mapped these rocks as Jurassic hornfels derived primarily from volcanic tuffs, tuff breccia, and lava flows. Farther to the south, in the Saddlebag Lake area, hornfels containing abundant quartz and feldspar, calc-silicate hornfels, and carbonaceous marble (map units PPNhcl, PZms) form a northwest-trending belt extending from Tioga Crest to Parker Peak, south of Mono Pass (Bateman et al. 1983; Huber et al. 1989).

East of Virginia Peak, a band of Jurassic-aged metamorphic rock units includes biotite-hornblende schist, phyllite, hornfels, and marble (map units Jas, Jrtp, Jqhm). Along the southeastern border of Yosemite National Park, metavolcanics (map unit Jbr) extend into the park from the Ritter Range. Mapped as Jurassic units, some of these rocks have been radiometrically dated to about 100 million years ago, in the younger Cretaceous Period (Huber 1989; Huber et al. 1989). Cretaceous metavolcanic rocks (map unit Kmva) at the summit of Mount Dana are about 118 million years old and derived from volcanic tuff, tuff breccia, and minor lava flows (Huber et al. 1989). Similar rocks have been mapped at Merced Peak in the Clark Range and at Sing Peak (Huber et al. 1989).

The metamorphic volcanic rocks of Cretaceous age (map units Kmv, Kmva, and Kmr) were not subjected to major deformation after their eruption. In addition, the age of these rock units suggests that they erupted from volcanoes at about the same time that some of the smaller plutonic rock suites were forming at depth (Huber 1989). Volcanic rocks associated with Mesozoic pluton emplacement are scarce in Yosemite National Park. These units may be among the few rocks that indicate corresponding volcanism at the time of Sierra Nevada Batholith formation.

May Lake Quartzite

Located at the eastern base of Mt. Hoffman, May Lake fills a narrow, northeast-trending depression carved by glaciers into highly jointed metamorphic quartzite (map units PZmsq, pKcs, and pKq; fig. 20). The exposure is about 2 km (1.2 mi) long by 0.3 km (0.19 mi) wide and separates two Cretaceous-aged plutons. The Granodiorite of Mount Hoffman (map unit Kmh) borders the quartzite to the west, and the Granodiorite of Kuna Crest (mapped as Tonalite of Glen Aulin, map unit Kgla) borders the quartzite to the east. The Granodiorite of Kuna Crest grades into the Half Dome Granodiorite (Huber et al. 1989; Glazner and Stock 2010). Similar quartzite is found at Snow Lake, located near the northern boundary of the park (Schweickert and Lahren 1991).

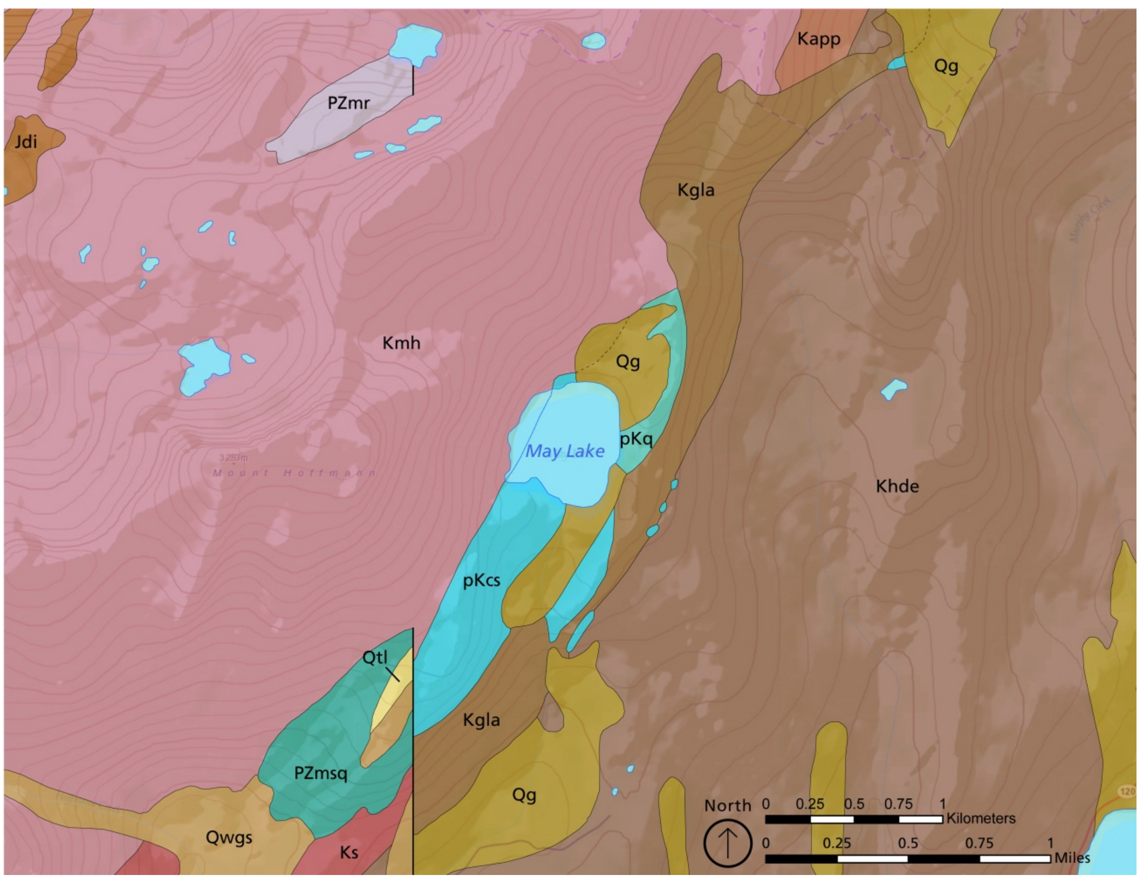


Figure 20. Simplified geologic map of the May Lake region. May Lake fills a depression formed in highly jointed metamorphic rocks, primarily white and grayish brown quartzite (PZmsq, pKcs, and pKq). The sandstone that metamorphosed to quartzite was originally deposited in near-shore, marine environments about 600–500 million years ago when the May Lake area was located far from the coast, raising the question of how the sandstone/quartzite came to be in this location. Thick black lines indicate a quadrangle boundary. See Map Unit Properties Table A for a description of the remaining geologic units. Graphic by Rebecca Port (Colorado State University) using Geologic Resources Inventory digital geologic data (see Geologic Map Data section).

The white to grayish-brown quartzite is composed almost entirely of quartz and is similar in composition and age to sandstones deposited farther east, such as the Tapeats Sandstone in Grand Canyon National Park and the Zabriskie Quartzite in Death Valley National Park (Middleton and Elliott 1990; Martin and Walker 1991; Mount et al. 1991; Glazner and Stock 2010). These sandstones, deposited between 600 and 500 million years ago, were part of a sandy shoreline that extended along the western margin of North America from southwestern Utah, through southern Nevada and western Arizona, to the Mojave Desert of southern California. West of this shoreline, shale, siltstone, and carbonate rocks of the same age record deposition in deep-marine, continental shelf environments (Stewart 1991). The conundrum to be solved at May and Snow lakes is how beach sand was deposited so far out to sea.

One explanation suggests that the ancient shoreline curved into the area, so that the quartzite exposures represent original sites of deposition. Another explanation suggests that the rocks at May Lake and Snow lakes were displaced about 400 km (250 mi) northward along a strike-slip fault (similar to today's San Andreas Fault) during the Early Cretaceous (Schweickert and Lahren 1991). The quartzite at May Lake has been subjected to at least four major episodes of deformation involving complex folding and faulting. Support for this interpretation comes from other exposures along the Sierra Nevada and comparable distances that rocks have moved along the San Andreas Fault (Martin and Walker 1991; Schweickert and Lahren 1991).

These slivers of metamorphic rocks in the central Sierra Nevada offer important clues about paleogeography (ancient geography) during the early history of the ancestral North American continent. Most of this history has been destroyed by the emplacement of the Sierra Nevada Batholith and subsequent erosion.

Volcanic Bedrock

From about 20 million to about 5 million years ago, extraordinary volumes of volcanic material erupted from volcanoes in the southern Cascade Range and buried the northern Sierra Nevada with lava flows, volcanic tuff, and lahars (volcanic mud flows). Some volcanic material reached as far south as the northern part of Yosemite National Park. The few exposures of Cenozoic volcanic rocks in the park erupted from 9 million to 3.5 million years ago (Huber et al. 1989). Like their plutonic counterparts, volcanic rocks are classified on the basis of composition and texture. Because they erupt onto Earth's surface and cool more quickly than plutonic rocks, they tend to be finer grained or even glassy. Few minerals are large enough to identify without a microscope. The volcanic rocks in Yosemite National Park contain little or no quartz and range from dacite to black basalt (table 3).

Table 3. Simplified classification of igneous rocks.

Volcanic rock	Si/O	Fe/Mg	Plutonic equivalent
Rhyolite	↑	↓	Granite
Dacite			Granodiorite
Andesite			Diorite
Basalt			Gabbro

Arrows indicate direction of increasing percentages of silica (Si/O) or mafic minerals containing iron (Fe) and magnesium (Mg).

Localized, erosional remnants of andesitic lahars of the Relief Peak Formation (map unit Trp) may be found near Kibbie and Frog creeks in the northwestern corner of the park and at Rancheria Mountain in the north-central part of Yosemite (Huber et al. 1989). About 10 million years ago, volcanic mudflows filled the Tuolumne River, forcing it to cut a new channel. The Tuolumne River currently lies more than 460 m (1,500 ft) below the mudflows, indicating the amount of channel incision since the volcanic activity (Huber 1989). These exposures are not easily accessible to visitors.

The Glen Aulin trail provides easier access route to a black volcanic outcrop known as the Little Devils Postpile (map unit Tbo), located on the south side of the Tuolumne River approximately 6 km (4 mi) from Tuolumne Meadows (fig. 21). The Little Devils Postpile consists of andesitic lava that solidified within a volcanic conduit feeding an ancient volcano that erupted about 8 million or 9 million years ago (Huber 1989; Glazner and Stock 2010). Mount St. Helens, Mount Rainier, and many other volcanoes in the Pacific Northwest's Cascade Range consist of andesite, which takes its name from the Andes Mountains in South America. Like basalt, andesite is dark, but it contains more silicon, potassium, and sodium than basalt.

Like its larger namesake in Devils Postpile National Monument (Graham 2009), the Little Devils Postpile displays exceptional columnar jointing (fig. 21). Columns (horizontal along the river gorge) formed parallel to the direction of heat flow out of cooling magma into adjacent, colder Cathedral Peak Granodiorite (Glazner and Stock 2010). As the lava solidified and contracted, cracks broke the rock into the roughly hexagonal pattern characteristic of columnar jointing.

Volcanic activity about 3.5 million years ago and subsequent erosion left exposures of basaltic lava south of the park near Cora Lakes and Miller Meadow Campground (map unit Ttb). Volcanism returned to the region about 700,000 years ago, when cataclysmic eruptions created the 16- by 32-km (10- by 20-mi)- wide Long Valley caldera, ejecting approximately 2,500 times as much ash as the 1980 Mount St. Helens eruption, which was blown eastward as far as Nebraska. Episodic eruptions have occurred over the past few thousand years from the Mono Craters and Inyo domes. The most recent dome formed about 600 years ago (Huber 1989). Volcanic deposits from these eruptions lie east and south of Yosemite National Park

Figure 21. Little Devils Postpile, Yosemite National Park, exposed along the south side of the Tuolumne River. Remnant of a conduit carrying andesitic lava, the feature contains columnar joints that formed as the magma cooled. National Park Service photograph courtesy of Greg Stock (Yosemite NP).

Rockfalls, Rockslides, and Talus Piles

Rockfalls are the most active geologic process operating in Yosemite National Park today; they continue to modify and shape the canyons. More than 600 rockfalls have been recorded in the park since 1857 and thousands of tons of rock tumble into Yosemite Valley each year (Glazner and Stock 2010). Certainly, more rockfalls have gone unrecorded. Since the Tioga-aged glacier retreated from the Valley about 15,000 years ago, rockfall debris (talus) has accumulated at the base of almost every cliff in Yosemite Valley as a result of glacially steepened cliffs, fractured rocks, severe winter storms, freezing temperatures, earthquakes, and other triggering mechanisms (refer to the Geologic Issues section). In some areas, avalanche chutes funnel debris into tremendous cones of talus (fig. 22).

In 1872, John Muir witnessed the Eagle Rock rockfall, triggered by the 1872 Owens Valley earthquake and one of the larger rockfalls in Yosemite's recorded history. Quite impressed by the rockfall, Muir described the event as:

> *Then, suddenly out of the strange silence and strange motion there came a tremendous roar. The Eagle Rock on the south wall, about a half a mile up the Valley, gave way and I saw it falling in thousands of the great boulders I had so long been studying, pouring to the Valley floor in a free curve luminous from friction, making a terribly sublime spectacle – an arc of glowing, passionate fire, fifteen hundred feet span, …the sound was so tremendously deep and broad and earnest, the whole earth like a living creature seemed to have at last found a voice…* John Muir (1912, p. 58–59).

About 59,000 tons of rock fell, an estimated volume that could fill 25 four-bedroom houses (Glazner and Stock 2010).

Rock Climbing Related Features

Rock climbers flock to Yosemite National Park to explore the vertical wilderness created by the granitic domes, monoliths, spires, and cliffs. At 1,000 m (3,300 ft) high, the nearly vertical El Capitan is one of the most popular and challenging climbs in the world (Glazner and Stock 2010). Half Dome rises 1,443 m (4,733 ft) from the valley floor. The following smaller-scale geologic features render these seemingly insurmountable, sheer structures climbable (Glazner and Stock 2010):

- Splitter cracks
- Flakes
- Dihedrals
- Dikes
- Chickenheads
- Megacrysts
- Slabs
- Boulders.

Splitter cracks

Splitter cracks are long cracks in granite faces that maintain remarkably uniform widths, although they are not as extensive as joints. The cracks form primarily due to exfoliation wherein curved, shell-like slabs of rock detach from the main mass along exfoliation joints (see Joints section). Using a technique appropriately called jamming, climbers jam their hands and feet into the cracks. Classic splitter climbs in Yosemite include "The Grack" below Glacier Point, "Reed's Pinnacle Direct" above the Big Oak Flat Road, and "Sons of Yesterday" near Royal Arches beneath North Dome (Glazner and Stock 2010).

Flakes

Exfoliation also produces flakes, slabs of rock that remain temporarily attached to the cliff and may spall off at any time. Using a technique called laybacking, climbers grasp the edge of a flake, place their feet high on the cliff, lean out, and climb hand over hand up the flake. Examples of flake climbs in Yosemite include "Wheat Thin" on Cookie Cliff and "Hermaphrodite Flake" on Stately Pleasure Dome above Tenaya Lake. "Boot Flake" and "Texas Flake" are two impressively large flakes on the Nose Route of El Capitan (Glazner and Stock 2010).

Dihedrals

When a slab of rock falls, a dihedral angle (the angle between two planes) forms where the two adjacent walls on the fresh surface meet, which climbers call an open book. The exfoliation joint that was behind the slab before it fell is usually exposed at the corner of a dihedral, and climbers ascend along the crack by bridging (placing one hand and one foot on each face), jamming, or laybacking. Popular dihedral climbing routes are found at "Five Open Books," west of Lower Yosemite Fall, and "Great White Book" adjacent to Tenaya Lake (Glazner and Stock 2010).

Dikes

Igneous dikes, common in Yosemite's granitic rocks, form linear bands that are roughly 0.3 m (1 ft) thick. On the east face of El Capitan, dikes of dark, fine-grained diorite cut across El Capitan Granite. Dikes and irregular masses of diorite also intrude Taft Granite. Because they are more resistant to weathering and erosion, dikes often protrude from the surrounding granite. Dike climbing can be dangerous because these features are not associated with cracks. Climbers' only protection is provided by drilling bolts into the rock, which is permitted in Yosemite National Park if done by hand. Examples of dike climbs in Yosemite include "Snake Dike" on the southwest face of Half Dome and the "Dike Route" on Pywiack Dome near Tenaya Lake (Glazner and Stock 2010).

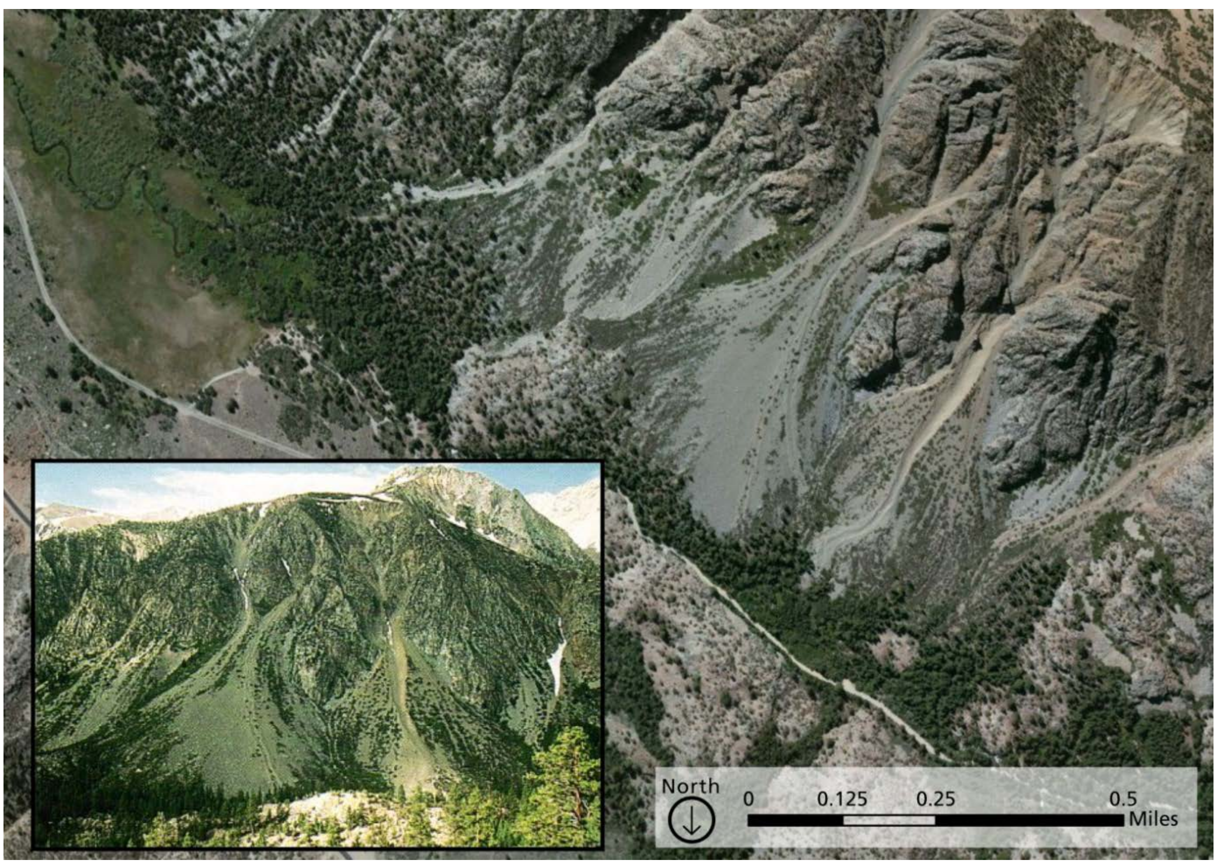


Figure 22. Avalanche chutes and talus cones in Lee Vining Canyon, east of Tioga Pass. Graphic by Rebecca Port (Colorado State University). U.S. Geological Survey inset photograph from Huber (1989, fig. 84), available at http://www.yosemite.ca.us/library/geologic_story_of_yosemite/ (accessed February 16, 2011).

Chickenheads

Like dikes, enclaves in the El Capitan Granite (map unit Kec) are often more resistant to erosion and weathering and protrude from the surrounding rock. Climbers use these dark blobs, referred to as chickenheads (fig. 23), as handholds and footholds. Chickenhead climbs in Yosemite can be found along the western exposures of the El Capitan Granite and include "Sloth Wall," "Boneheads," and "Fun Terminal" in Merced Gorge (Glazner and Stock 2010).

Figure 23. Chickenheads on the "Killer Pillar" route at Elephant Rock. NPS photograph courtesy of Greg Stock (Yosemite NP).

Megacrysts

Large, rectangle orthoclase phenocrysts (megacrysts) in the Cathedral Peak Granite (map unit Kcp) also protrude from rock surfaces because they are more resistant to weathering than the surrounding fine-grained groundmass, but they are smaller than chickenheads (fig. 24). As they do with chickenheads, climbers use megacrysts for handholds and footholds. Examples of megacryst climbs include the world renowned "Southeast Buttress," "Golfer's Route" near Tenaya Lake, and the exceptionally difficult "Bachar-Yerian Route" near Tuolumne Meadows (Glazner and Stock 2010).

Figure 24. Megacryst knobs in Cathedral Peak Granite on a dome near Tuolumne Meadows. NPS photograph courtesy of Greg Stock (Yosemite NP).

Slabs

The expansive, sloping slab of rock below Glacier Point, known as the Glacier Point Apron, is a popular slab climbing location in Yosemite National Park (fig. 25). When the glacier retreated from Yosemite Valley following the end of the Tioga glaciation, it left behind this smooth, low-angled slab of rock, which forms the lower portion of the characteristic, glacially- carved U-shaped profile. In slab climbing, climbers rely on their body weight (and sticky rubber soles on climbing shoes) to keep them anchored to the rock. Because cracks are rare in slabs, climbers use bolts as in dike climbing. Unique climbing challenges can also be found on the other aprons in Yosemite National Park. Popular slab climbs on the Glacier Point Apron include "Marginal," "Goodrich Pinnacle," and "The Cow" (Glazner and Stock 2010).

Figure 25. The smooth and glacially polished slabs of the Glacier Point Apron are popular for slab climbing. White arrow marks the transition between the smooth, glacier-polished slab and rough exposures lacking evidence of glacial impact, indicating the height of the Tioga-aged glacier. NPS photograph courtesy of Greg Stock (Yosemite NP). Annotation by the author.

Boulders

Rockfalls in Yosemite National Park provide an excellent opportunity to pursue the sport of bouldering, the free-climbing of boulders, rather than cliff faces, without the use of ropes or other gear (fig. 26). Large boulders, some the size of small buildings, have come to rest on the valley floor after travelling long distances from cliff bases during a rockfall. In general, spherical boulders have travelled farther than angular boulders of similar volume. Perhaps the most famous bouldering route in the world is on the Columbia Boulder in the middle of Camp 4 (Glazner and Stock 2010).

Figure 26. Climbers on the Columbia Boulder in Camp 4. Like most other boulders in Yosemite Valley, this boulder resulted from a rockfall. NPS photograph courtesy of Greg Stock (Yosemite NP).

Joints

Joints, which are fractures or breaks in rock surfaces, may be the primary bedrock feature influencing the landscape of Yosemite National Park. In the relatively homogeneous, erosion-resistant granitic terrain of the Sierra Nevada, joints provide zones of weakness that allow for increased erosion and weathering. Major landscape features such as the planar face of Half Dome, the parallel cliffs at Cathedral Rocks, the faces of the Three Brothers (fig. 27), and even linear stretches of mountain streams are controlled by local and regional joint patterns. Smaller, outcrop-scale joints determine local surface patterns and rates of rock erosion. For example, intersecting joints in El Capitan Granite form a rectangular pattern (fig. 28).

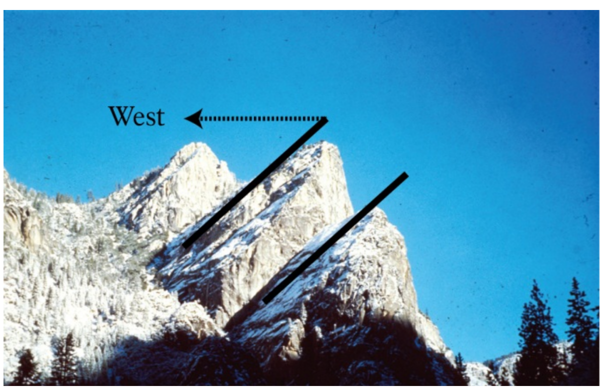


Figure 27. Regional joints (solid black lines) determined the westward slope of the upper surfaces of the Three Brothers. U.S. Geological Survey photograph from Huber (1989, fig. 34), available at http://www.yosemite.ca.us/library/geologic_story_of_yosemite/ (accessed February 16, 2011). Annotation by the author.

Bedrock composition and texture influence joint spacing, which is generally wider in quartz-rich, coarser-grained rocks (granite and granodiorite) than in less siliceous, finer-grained rocks (tonalite and diorite). The fine-grained Diorite of the Rockslides, for example, contains the most closely-spaced joints in Yosemite Valley, and these joints promote frequent cliff collapse resulting in talus piles at the base of the Rockslides (Huber 1989). A short distance to the east, the largely unbroken face of El Capitan presents one of the sheerest cliffs in the world, contrasting sharply with the rubbly slopes of the Rockslides (fig. 29). Pillars, columns, and pinnacles form from the erosion of closely spaced joints. Examples in Yosemite Valley include Watkins Pinnacle, Split Pinnacle, Washington Column, and Cathedral Spires.

Figure 28. Intersecting vertical joints have formed rectangular blocks in this outcrop of El Capitan Granite. U.S. Geological Survey photograph from Huber (1989, fig. 36), available at http://www.yosemite.ca.us/library/geologic_story_of_yosemite/ (accessed February 16, 2011).

The most common regional joint set patterns in the High Sierra consist of vertical, nearly orthogonal northwest- and southwest-trending joints. The joints cut across boundaries between individual granitic plutons, indicating that they formed after the batholith was emplaced (Huber 1989). They may have formed from tectonic stresses that accompanied the tilting of the entire Sierra Nevada region.

Exfoliation joints are the primary joint type responsible for many of Yosemite's famous landmarks (fig. 30). These joints, also called unloading or sheeting joints, form concentric, sheet- and onion-like layers in Yosemite's granitic rocks. They provide conduits for groundwater and play a significant role in triggering rockfalls (Stock et al. 2012a, 2012b). During the ice ages, exfoliation joints allowed glaciers to more easily erode the bedrock surface.

Currently, various weathering agents dislodge, or exfoliate, the sheet-like layers from the main rock body. Plant roots grow in cracks that develop perpendicular to exfoliation joints, prying them apart. Water in the cracks expands upon freezing, applying more pressure to the joints. Over time, water chemically reacts with the adjacent granitic rock, carrying away some dissolved minerals and enlarging cracks (Glazner and Stock 2010).

The origin of exfoliation joints has fascinated geologists for more than a century. Granitic rocks crystallize under great pressure deep within the Earth. Perhaps the most widely held hypothesis, included in textbooks for decades, suggests that exfoliation joints form when this confining pressure is released by erosion of overlying

Figure 29. Diorite of the Rockslides (the slope to the left of El Capitan) forms a jumble of talus blocks due to failure along closely- spaced joints. In contrast, El Capitan granite (right) is largely unjointed and the debris pile of debris at the cliff base is relatively small. National Park Service photograph courtesy of Greg Stock (Yosemite NP).

Figure 30. Exfoliation (sheeting) joints along Tioga Road west of the Yosemite Creek crossing formed in Yosemite Creek and Sentinel granodiorites (map units Kyc and Ks). National Park Service photograph courtesy of Greg Stock (Yosemite NP).

rock and sediment, increasing tensile (pull-apart) stress and opening the joint vertically (Calkins et al. 1985; Huber 1989).

However, simple relief of compressive stress will not open large fractures in massive rock bodies (Martel 2004, 2006, 2011). Most eroded terrains contain no sheeting joints, and erosion typically does not produce the tensile stress perpendicular to Earth's surface required to open such joints. Martel (2006, 2011) explained that sheeting joints occur primarily in strong, dense rocks, such as granite, that have convex surfaces and are under strong horizontal compression. Using equilibrium equations involving normal and tensile stresses, slope of the rock surface, rock density, gravity acceleration, and other mathematical components, Martel illustrated that sheeting joints develop in massive rocks under intense horizontal compression. When curvature is sufficient and compression overcomes both the force of gravity and the strength of the rock, as Glazner and Stock (2010) summarized, horizontal compression pushes the convex rock surface upward, creates tensile stress perpendicular to the surface at depth, and opens joints parallel to the convex surface (fig. 31).

Figure 31. Formation of exfoliation joints, as illustrated by Glazner and Stock (2010, p. 152) using a piece of sourdough bread. Two curved slits cut parallel to the convex upper surface (upper photograh) open when the bread is squeezed from the sides (lower photograph), illustrating how horizontal compression combined with a curved surface generates vertical tensile stress and, ultimately, exfoliation joints. Photographs courtesy Greg Stock (Yosemite NP).

Questions about sheeting joint formation persist, including the nature of their interaction and propagation (Stock et al. 2012b), the distances they extend, and their presence in slopes that are now concave (Martel 2006). Yosemite National Park provides an excellent outdoor laboratory in which to study these issues.

Regardless of how they form, exfoliation joints have generated impressive structures in Yosemite National Park. Noteworthy examples can be found along the Tioga Road near Yosemite Creek (fig. 30) in Yosemite Creek and Sentinel granodiorites (map units Kyc and Ks). Extensive sheet jointing characterizes the coarse-grained El Capitan Granite (map unit Kec) exposed on the southern slope of Mt. Hoffman, and eroded remnants of sheets are exposed in El Capitan Granite on the flank of Sentinel Dome (Glazner and Stock 2010).

Pleistocene Glacial Features

Pleistocene (ice-age) alpine glaciers dramatically modified the landscape of Yosemite National Park and the rest of the High Sierra. The dozens of glacial advances that occurred during the past 2 million years in the Sierra Nevada may be grouped into five major periods of glaciation (table 4). In the Pleistocene, the Sherwin, Tahoe, and Tioga glaciations created the famous landscape and iconic features of Yosemite National Park (see the Geologic History section). The extent of each glaciation is difficult to determine because glacial advances may destroy evidence of previous advances. The Tahoe glaciation may have reached its maximum extent in two phases, 50,000 to 42,000 and 200,000 to 140,000 years ago, the younger of which was mapped in Sequoia and Kings Canyon National Parks (Clark et al. 2003; Moore and Mack 2008).

Table 4. Simplified glacial history of the Sierra Nevada.

Glaciation	Approximate Time Frame
Matthes (Little Ice Age)	1350–1850 C.E.
Tioga	26,000–18,000 years ago
Tahoe	140,000–80,000 years ago
Sherwin	800,000 years ago
McGee	1.5 million years ago

The map of glacial and postglacial deposits in Yosemite Valley (Matthes 1930) used older terminology for different periods of ice. Refer to Map Unit Properties Table B (in pocket).

The majority of prominent glacial features (both erosional and depositional) in Yosemite National Park are the result of the Tioga glaciation (table 5).

Table 5. Glacial features in Yosemite National Park described in the text.

Erosional Features
Glacial polish and abrasion
Roches moutonnées
U-shaped valleys
Hanging valleys
Cirques
Arêtes, horns, and cols
Overdeepenings and tarns
Rock drumlins
Potholes

Depositional Features
Till
Moraines
Outwash
Kettles
Erratics

Erosional Features

Glaciers are extremely effective agents of erosion through two primary processes: abrasion (and polishing), which occurs in relatively crack-free bedrock susceptible to the effects of glacial ice and water, and plucking, which occurs where cracks facilitate the removal of bedrock material. Rocks, sand, and other grit embedded in the base of glacial ice abrade and polish bedrock (fig. 32). Debris-laden ice may also gouge striations (parallel lines) in the bedrock. These can be used to determine flow direction of the glacier (parallel to the striations). Larger rock debris may leave chatter marks (crescent-shaped gouges) in the bedrock. The horns of the crescents point in the opposite direction of glacial advance.

Figure 32. Glacial striations and chatter marks. Striations (lines) on the rock surface parallel the direction of glacier flow and the horns of crescent-shaped chatter marks point in an up-glacier direction, indicating that ice flowed from the upper- right to the lower- left of this view (black arrow). National Park Service photograph courtesy of Greg Stock (Yosemite NP). Annotation by the author.

Impressive glacial polish in the massive units of Cathedral Peak Granodiorite (map unit Kcp) and El Capitan Granite (map unit Kec) in the Tuolumne River Valley and Tenaya Canyon formed because the hard, granitic rocks were relatively free of cracks, facilitating the glaciers' smooth passage over the bedrock (Düehnforth et al. 2010; Glazner and Stock 2010).

Plucking (also called quarrying) significantly modifies glacial landscapes. This process requires the presence of water at the base of the glacier as the result of surface water transport through crevasses or moulins (sinkholes in the ice) or the pressure melting of ice in contact with bedrock. Water enters joints and cracks and freezes, shattering the rock. Broken fragments are then carried away by the glacier. Plucking may also occur due to large pressure gradients that develop as ice slides over a bedrock step.

Roches moutonnées (also called whalebacks or sheepbacks), are bedrock knobs with distinctly asymmetrical profiles that display evidence of both abrasion and plucking. The term was coined by Horace-Bénédict de Saussure, an 18th-century French alpine explorer who thought the rocks (roches) looked like fashionable wigs of the day that were smoothed with mutton fat (moutonnée) to keep the hair in place. Excellent examples of roches moutonnées are Lembert and Pothole domes, in the Tuolumne Meadows area (fig. 33). Abrasion smoothed and polished the stoss, or upstream, side while glacial plucking resulted in a steep, jagged lee side.

U-shaped valley profiles are among the most obvious glacial features in Yosemite National Park. Whereas mountain streams tend to create V-shaped alpine valleys because erosional power is focused in relatively narrow channels, glaciers occupy the entire valley and cause both lateral and vertical erosion, widening and deepening valleys. The plucking and grinding actions of glaciers modify these alpine valleys by removing all unconsolidated sediment and cutting a relatively flat-bottomed, steep-walled, straight U-shaped profile (fig. 34).

Lyell Canyon near Tuolumne Meadows is a good example of a U-shaped, glacially-carved canyon with steep walls and a bedrock floor. Although Yosemite Valley was formed by the same processes as classic U-shaped valleys, it has a relatively flat floor filled with up to 610 m (2,000 ft) of sediment burying the base of the "U" (fig. 35; Glazner and Stock 2010).

Figure 33. Glaciers carved Pothole Dome, a rouche moutounnée in Cathedral Peak Granodiorite (map unit Kcp) on the west side of Tuolumne Meadows, flowed from right (stoss side) to left (lee side) of this view (black arrow). National Park Service photograph courtesy of Greg Stock (Yosemite NP). Annotation by the author.

Figure 34. U-shaped valley. Glaciers carved Parker Creek canyon into a U-shaped valley, characteristic of large-scale alpine glacial erosion. Parker Lake (foreground) fills a depression gouged into bedrock by the advancing glacier. Upon retreating, the glacier left a recessional moraine that partially dams the canyon. National Park Service photograph courtesy of Greg Stock (Yosemite NP).

Some U-shaped valleys can be seen hanging high on the cliffs of Yosemite Valley, Grand Canyon of the Tuolumne River, and other main valleys in the Sierra Nevada. The main trunk systems contained thick glaciers that eroded and cut much deeper valleys than did smaller glaciers in tributary valleys. When the ice melted, these tributary valleys, known as hanging valleys, were left high on the canyon walls. Their streams now form waterfalls to the main valleys below. With a free-fall of 189 m (620 ft), Bridalveil Fall is a classic example of a waterfall emerging from a hanging valley (fig. 3).

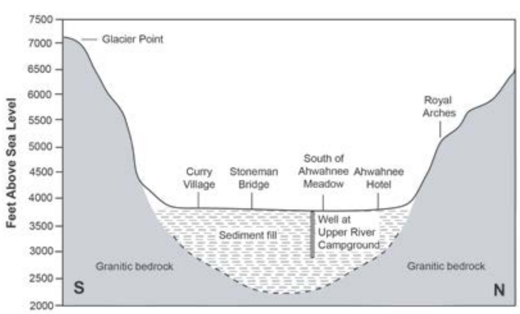
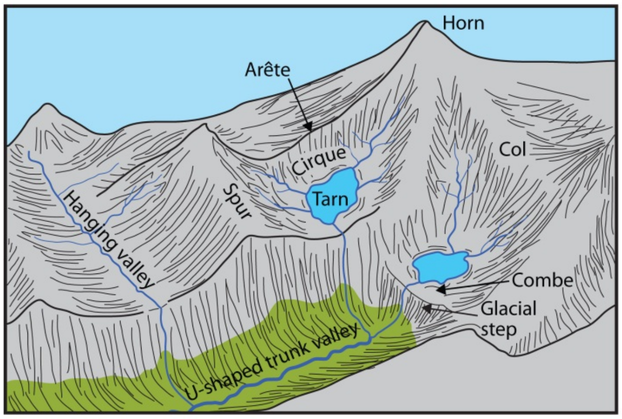


Figure 35. Cross section of the overdeepening of eastern Yosemite Valley based on seismic imaging and well data. Glaciers carved the U-shaped valley profile, and as much as 610 m (2,000 ft) of sediment filled the overdeepening after the glaciers retreated. Rockfall and rivers added sediment and debris to the valley. National Park Service diagram courtesy of Greg Stock (Yosemite NP).

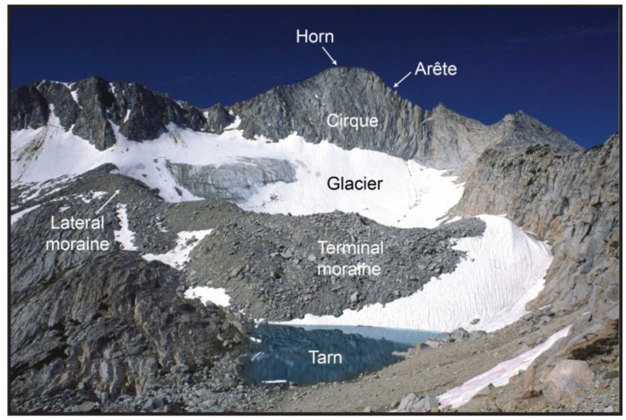
Glaciers gouged hundreds of bowl-shaped depressions, called cirques, at the bases of serrated ridges and mountain peaks in the Sierra Nevada (fig. 36). In the summer, when no new snow accumulates, ice pulls away from the rock at the head of a glacier, forming a great crevice known as a bergschrund (fig. 36). Water enters the bergschrund, flows into fractures in the rock, and freezes in the winter. Rocks dislodged at cliff bases due to freezing and thawing are subsequently frozen into the main mass of the glacier and transported out of the cirque, thereby enlarging the depression.

Freeze–thaw action continues to quarry cliffs above cirques. As the opposite sides of a ridge narrow, they form a jagged ridgeline known as an arête. Horns are sharp peaks that form where jagged arêtes branch (fig. 36). Matterhorn Peak, the most notable horn in Yosemite National Park, is named for Switzerland's famous horn, the Matterhorn. A col forms where headward erosion forms a pass in the arête between two cirques.

Many cirques in Yosemite National Park contain tarns, small lakes that fill ice-carved depressions. Tarns are the most common type of alpine lake and their distribution in Yosemite National Park coincides almost exactly with the extent of glacial coverage (Glazner and Stock 2010). The deep basins carved by alpine glaciers are called overdeepenings, which filled with water when the glaciers retreated (Glazner and Stock 2010).



A. Schematic diagram of alpine glacial features



B. Glacial features on Mt. Conness

Figure 36. Glacial features. A. Schematic diagram of alpine glacial features. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), modified by Rebecca Port (Colorado State University). B. Glacial features associated with the northeast side of Mt. Conness including the glacial horn, arêtes, and cirque headwall carved by previous Pleistocene glaciers and the lateral and terminal moraines associated with the modern Conness Glacier. A tarn (glacial lake) fills the cirque basin. National Park Service photograph courtesy of Greg Stock (Yosemite NP).

Yosemite Valley is a particularly large overdeepened U-shaped valley filled with sediment instead of water (fig. 35). The valley is deepest near the Ahwahnee Hotel, where the elevation of the present valley floor is about 1,220 m (4,000 ft). Seismic imaging shows that the valley becomes shallower near the Three Brothers, deepens again near El Capitan, and then becomes shallower downstream from the Pohono Bridge. From the Pohono Bridge to the town of El Portal on the western edge of the park, the Merced River drops in elevation about 610 m (2,000 ft). One way to imagine the overdeepening of Yosemite Valley is to consider that the bedrock valley floor lies at about the same elevation as El Portal [about 610 m (2,000 ft)].

Rock drumlins for when glaciers pluck and carve fractured rock into a long, low, rounded form. These features, which resemble giant baguettes, are oriented parallel to the flow of the glacier (Glazner and Stock 2010). The white quartzite at May Lake is a very good example of a rock drumlin, indicating an approximate north–south direction of flow.

Glaciers generate a tremendous amount of meltwater. Water flowing at the base of a glacier eroded potholes on the southern end of Pothole Dome in Tuolumne Meadows, the edges of which were further eroded and smoothed by sediment caught in the swirling meltwater. Blocks plucked by the glacier fell into the potholes and eroded them more deeply. Constant churning rounded the edges of the blocks until they became boulders. Today, the deep cylindrical potholes contain boulders that are 1–1.2 m (3–4 ft) in diameter (fig. 37; Glazner and Stock 2010).

Figure 37. Pothole on the south side of Pothole Dome, Tuolumne Meadows. Glacial meltwater scoured this and other potholes and deposited the large, light-colored, rounded boulder (arrow) of Johnson Granite Porphyry (map unit Kjp) that is partially covered by shadows in the foreground. The boulder is about 1.2 m (4 ft) in diameter. National Park Service photograph courtesy of Greg Stock (Yosemite NP). Annotation by the author.

Depositional Features

Unconsolidated glacial debris also forms distinct landforms in Yosemite National Park. Glaciers transport all sizes of debris, from fine silt termed "rock flour" to boulders, depositing it along the sides and at the farthest extents of the glaciers and on the valley floors. Whereas sediment in a river is sorted according to the river's velocity and overall capacity to carry a specific load, leaving sorted, stratified deposits, glaciers dump debris in unsorted piles of fine- to coarse-grained rock debris termed glacial till (fig. 38).

Figure 38. Glacial till exposed along the Tioga Road at Siesta Lake. The till consists of an unsorted mixture of boulders, sand, and clay that was left behind when the glacier retreated. U.S. Geological Survey photograph available in Huber (1989, fig. 60) and at http://www.yosemite.ca.us/library/geologic_story_of_yosemite/ (accessed April 12, 2012).

Deposits of till form lateral, terminal, recessional, and ground moraines (fig. 39). Lateral moraines consist of till deposited along glacial margins. Terminal moraines mark the farthest advance of a glacier. The non-distinct, hummocky topography characteristic of ground moraines forms from till deposited beneath a glacier. Recessional moraines develop as a glacier retreats in its characteristically haphazard manner of starts-and-stops. Matthes (1930) mapped moraines associated with different glaciations throughout Yosemite Valley (refer to Geologic Map Overview Graphic sheets 3 and 4, and Map Unit Properties Table B).

Deposits of Tioga and Tahoe till (map units Qti and Qta) are located throughout Yosemite National Park (Huber et al. 1989). In general, moraines of Tioga Till are relatively sharp-crested with abundant boulders at the surface, whereas the older Tahoe Till forms moraines with subdued crests and scattered, weathered boulders at the surface (Huber et al. 1989). In Yosemite Valley, the ridge east of Bridalveil Meadow, generally considered to be the terminal moraine of the Tioga glacier, lies down-valley from the recessional moraine that forms the more visible ridge west of El Capitan Meadow (Glazner and Stock 2010). West of the Bridalveil Meadow moraine, the valley undergoes a dramatic change from a glacially-carved, U-shaped valley to a V-shaped profile characteristic of valleys incised by rivers.

The smoothly convex El Capitan moraine extends across Yosemite Valley at the western end of El Capitan Meadow. This long, narrow, north–south trending moraine contains a variety of rock types and sizes in the Tioga Till including boulders of Cathedral Peak Granodiorite that are too large to have been transported by the Merced River. The nearest bedrock outcrop of Cathedral Peak Granodiorite lies about 19 km (12 mi) east of the El Capitan moraine (Glazner and Stock 2010).

When the glacial till was deposited, the El Capitan recessional moraine formed a natural dam across Yosemite Valley. Shallow lakes likely formed behind the dam when the glacier melted, and these eventually filled with sediment. The Merced River gradually eroded a gap in the dam and removed all sediment except large boulders, which now partially block the channel and form small rapids. In the late 1800s, the rocks above the rapids were blasted in an effort to reduce winter and

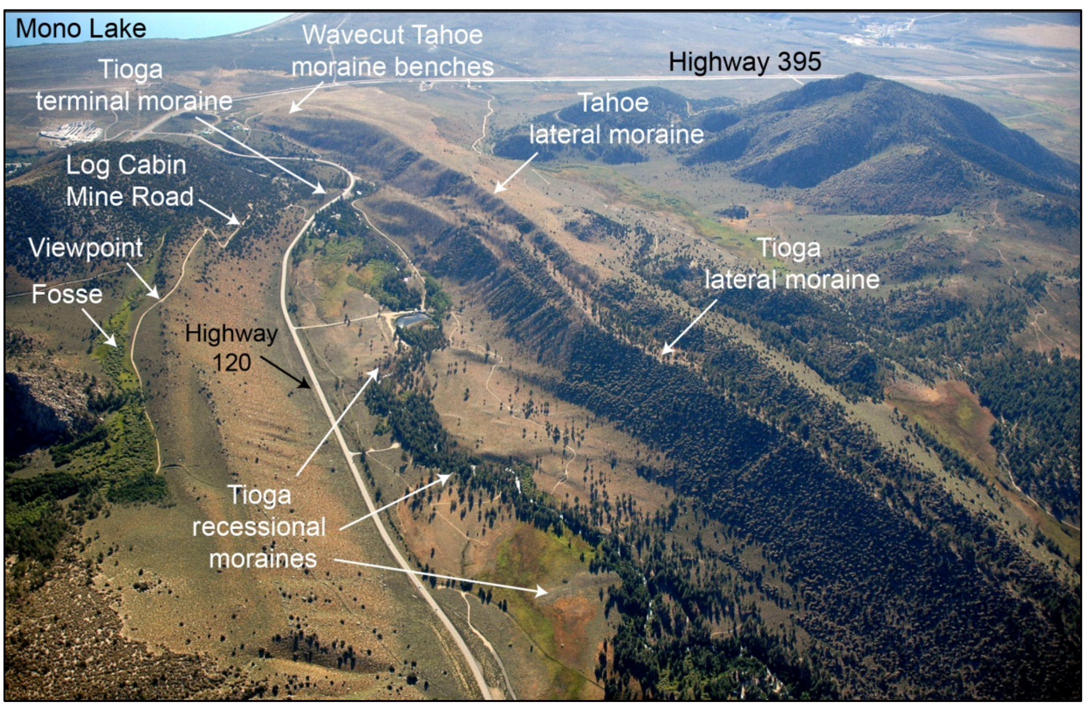


Figure 39. View to the east of moraine types left by alpine glaciers in Lee Vining Canyon, east of the park. Lateral moraines form along the side margins of a glacier, terminal moraines form at the glacier's farthest extent, and recessional moraines form during a pause in a glacier's retreat. National Park Service photograph with annotation courtesy of Greg Stock (Yosemite NP).

spring flooding. In addition to reducing flood frequency, the change lowered the river level, resulting in increased channel incision upstream that may have lowered groundwater levels, allowing the forest to encroach into the El Capitan Meadow near the river (Smillie et al. 1995). During yearly flooding, water still backs up behind the El Capitan moraine, which continues to profoundly affect the hydrology of Yosemite Valley (Glazner and Stock 2010).

During periods of glacial retreat, meltwater streams discharged outwash deposits of gravel, sand, and silt from the front of the glacier. Turbulent, high-velocity meltwater streams have removed most till and outwash deposits on the wetter western side of the Sierra Nevada. However, all moraine types have been preserved in Lee Vining Canyon, east of Yosemite National Park between Tioga Pass and Mono Lake (fig. 31B; Huber 1989; Glazner and Stock 2010). The canyon contains paired lateral moraines from the Tioga and Tahoe glaciations. The outer lateral moraine formed during the Tahoe glaciation, which peaked 140,000–80,000 years ago, and the inner lateral moraine formed as a result of the Tioga glaciation, which peaked about 20,000 years ago. The small, lush valley between the lateral moraines on the north side of the road is known as a fosse, which is also the name for a tributary stream that has been diverted by lateral moraines (fig. 39; Glazner and Stock 2010). The Tioga terminal moraine is exposed in a roadcut about 1.8 km (1.1 mi) west of the junction of California Highway 120 and U.S. Highway 395. At least six recessional moraines can be found on the relatively flat floor of the canyon.

As the Tioga glacier receded, it left behind blocks of ice buried by sediment. When the ice melted, water filled the depressions in the sediment, forming small kettle-shaped ponds. Some kettle ponds also formed behind recessional moraines. The kettle ponds in Dana Meadows were left behind by the Tioga-age glacier that once occupied Tioga Pass (Huber 1989; Glazner and Stock 2010).

Glacial retreat also left huge boulders, known as glacial erratics, throughout Yosemite National Park (fig. 40). Matthes (1930) mapped their locations throughout Yosemite Valley (Geologic Map Overview Graphic sheet 4). Transported by glacial ice away from their point of origin, these boulders may have an entirely different composition and texture than the bedrock upon which they lay. For example, boulders of Cathedral Peak Granodiorite, recognized by the characteristically large, pink orthoclase crystals, rest on bedrock composed of Half Dome Granodiorite (map unit Khd) along the western shore of Tenaya Lake. These boulders came from the eastern shore of the lake and Tuolumne Meadows. Glacial erratics composed of Cathedral Peak Granodiorite are scattered around the kettle ponds in Dana Meadows, but the bedrock consists of Granodiorite of Kuna Crest (map unit Kkc) and Half Dome Granodiorite. Field evidence indicates that the glacial erratics in Dana Meadows were transported over Tioga Pass by a glacier flowing from the Mt. Conness area, approximately 6 km (4 mi) north of the pass. The glacier was at least 60 m (200 ft) thick as it flowed over the pass (Glazner and Stock 2010).

Figure 40. This massive glacial erratic on Turtleback Dome near the western end of Yosemite Valley was deposited by an early glaciation, possibly the Sherwin. The boulder and underlying bedrock are composed of El Capitan Granite (map unit Kec). Evidence that the boulder is an erratic includes the nearly vertical aplite dike in the boulder that does not continue into the bedrock and the greater abundance of enclaves in the bedrock than in the boulder. Child for scale. A cobble of Cathedral Peak Granite in a nearby till deposit confirms the presence of glaciers in this area, as the nearest exposure of this granite is about 26 km (16 mi) up-valley in the upper Merced drainage. National Park Service photograph courtesy of Greg Stock (Yosemite NP).

Near the Olmsted Point parking lot, glacial erratics rest on polished and striated bedrock surfaces, clearly demonstrating that the boulders were deposited by glaciers. Other erratics are composed of Half Dome Granodiorite, which also forms the bedrock, indicating that they did not travel far. At the summit of Olmsted Point, boulders of the darker Granodiorite of Kuna Crest, which is mapped 34 km (21 mi) up-valley from Olmsted Point, are scattered on Half Dome Granodiorite bedrock (Glazner and Stock 2010).

Glacial erratics in Yosemite National Park provide excellent evidence for the areal extent of glaciers and the direction of ice flow. They help identify the glacial origin of subtle deposits that otherwise lack conclusive glacial evidence. For example, boulders of Cathedral Peak Granodiorite resting 2,300 m (7,500 ft) on the Diving Board on the western shoulder of Half Dome confirm a glacial origin for the unconsolidated material at this elevation (Glazner and Stock 2010).

Several older glacial erratics are perched on bedrock pedestals that likely formed due to exfoliation joints (fig. 41). Water entered the joints and freeze–thaw processes helped to detach bedrock slabs. The pedestals did not exfoliate because the erratics atop them sheltered the bedrock from weathering or because the weights of the boulders closed the exfoliation joints, effectively prohibiting freeze–thaw activity (Glazner and Stock 2010).

Nunataks

During the Tioga glaciation, glaciers did not completely cover the Sierra Nevada. Peaks and ridges that projected above the ice field are called nunataks. Glaciers carve and sharpen these bedrock islands as they pluck away at their sides. In the Tuolumne Meadows area, examples of nunataks include Cathedral Peak, Unicorn Peak, and Matthes Crest. The Dana Plateau and Rancheria Mountain became nunataks as the Tioga glaciers surrounded them, acting as ice-free sanctuaries for a variety of plants and animals, including a unique type of lupine found on the Dana Plateau (Glazner and Stock 2010).

Figure 41. Perched erratic. A boulder of knobby Cathedral Peak Granodiorite (map unit Kcp) rests on a pedestal of Half Dome Granodiorite (map unit Khd) on Moraine Dome near Little Yosemite Valley. Weathering and erosion have lowered the rock surface below the erratic by 1 m (3 ft), leaving the boulder perched on its pedestal. National Park Service photograph courtesy of Greg Stock (Yosemite NP).

Modern Glacial Features

The Lyell, Dana, and Maclure modern glaciers in Yosemite National Park are not remnants of Tioga (Pleistocene ice age) ice. When warming temperatures at the end of the Pleistocene and beginning of the Holocene reached a maximum about 5,000 years ago, most, if not all, glaciers in the Sierra Nevada had melted. Since then, global climate has fluctuated through warming and cooling cycles and at least three glaciations have occurred in the Sierra Nevada (Raub et al. 2006). Present-day glaciers belong to the most recent glaciation, the Matthes, which began about 500 years ago during the Little Ice Age (Huber 1989; Raub et al. 2006).

Features of these modern glaciers reflect the dynamic growth and retreat of alpine glaciers, both past and present. The accumulation and ablation zones, for example, record the balance between snow accumulation and melting (fig. 42). In the accumulation zone, accumulating snowfall eventually forms a dense, heavy snow known as firn. The weight of additional snow compacts the firn into ice, which becomes a glacier that begins to flow when it reaches a thickness of approximately 37 m (120 ft) (Glazner and Stock 2010). In the ablation zone, glacial ice is lost through melting or sublimation. If more ice accumulates than is lost, then the glacier will advance and move downslope. If not, the glacier will retreat upslope.

Bergschrunds, crevasses, and moulins (sinkholes in the ice) form on modern glaciers as they did in the past (fig. 42). Water entering these openings in summer lubricates the base of the glacier, allowing it to slide along the bedrock surface. Throughout the year, glacier deformation occurs as ice flows downhill due to its weight. To confirm this deformation process, John Muir used stakes to conduct motion experiments on the Maclure Glacier (Muir 1873; Basagic 2011). Deformation and sliding are the primary processes that move glaciers downslope. Evidence of sliding can be seen in a small ice cave at the end of the Maclure Glacier in Yosemite National Park (Glazner and Stock 2010).

The ice cave also illustrates how glaciers abrade and erode underlying bedrock. Where the Maclure Glacier contacts bedrock, small rocks that abrade and polish the rock are embedded in the ice. Chipped bedrock shows evidence of plucking (Glazner and Stock 2010).

The modern glaciers in Yosemite National Park and the High Sierra provide valuable field evidence that helps geologists decipher past glacial activity and project the future sustainability of the ice fields. Documentation of annual and seasonal changes in glaciers is critical as global climate change continues to melt the glaciers in the Sierra Nevada. Additional information is available in the Geologic Issues section.

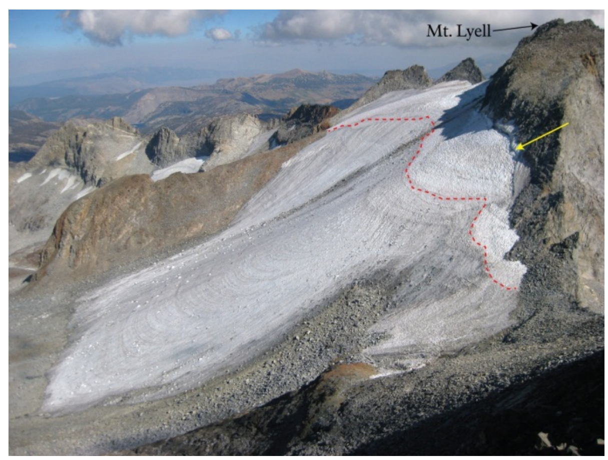


Figure 42. Geomorphic features of the Lyell Glacier, Yosemite National Park. Although it currently covers less than 0.65 km² (0.25 mi²), the Lyell Glacier is the largest glacier in the park and second largest in the Sierra Nevada. The dashed red line separates the accumulation zone (upper part of the glacier) from the ablation zone (area of snow and ice loss). The bergschrund is the large crack separating the ice from the bedrock (yellow arrow). A bergschrund forms each year as the glacier moves away from the cirque headwall. With an elevation of 3,997 m (13,114 ft), Mt. Lyell is the tallest peak in Yosemite National Park. National Park Service photograph courtesy of Greg Stock (Yosemite NP). Annotation by the author.

Waterfalls

Bedrock joints, stream erosion, and Pleistocene glaciers combined to produce the waterfalls in Yosemite National Park (table 6). More than 40 significant waterfalls cascade from the cliffs of Yosemite Valley alone. Prominent falls in the park include Bridalveil, Yosemite, Vernal, and Nevada (fig. 43; Glazner and Stock 2010). The origin of these waterfalls began with the uplift of the Sierra Nevada approximately 10 million years ago. Main streams, like the Merced and Tuolumne rivers, straightened along regional joint patterns. Stream gradients increased, and canyons such as Yosemite Valley and Grand Canyon of the Tuolumne River were incised much deeper than the valleys associated with their tributary streams. Pleistocene glaciers further straightened and deepened the main canyons, carving out steep walls from the jointed bedrock. When the glaciers retreated, streams cascaded from hanging valleys. Bridalveil Fall is the first spectacular waterfall that John Muir saw, and today's visitors see, upon entering Yosemite Valley (fig. 43A).

Table 6. Selected waterfalls in Yosemite National Park.

Waterfall	Height
Hanging Valley Waterfalls in Yosemite Valley	
Yosemite Falls	739 m (2,425 ft)
Ribbon Fall	491 m (1,612 ft)
Horsetail Fall	304 m (1,000 ft)
Bridalveil Fall	189 m (620 ft)
Illilouette Fall	113 m (370 ft)
Hanging Valley Waterfalls in Hetch Hetchy Valley	
Wapama Falls	457 m (1,500 ft)
Tueeulala Falls	304 m (1,000 ft)
Glacial Staircase (Joint Control Waterfalls)	
Staircase Falls	396 m (1,300 ft)
Nevada Fall	181 m (594 ft)
Vernal Fall	97 m (317 ft)

Source: National Park Service (2011h).

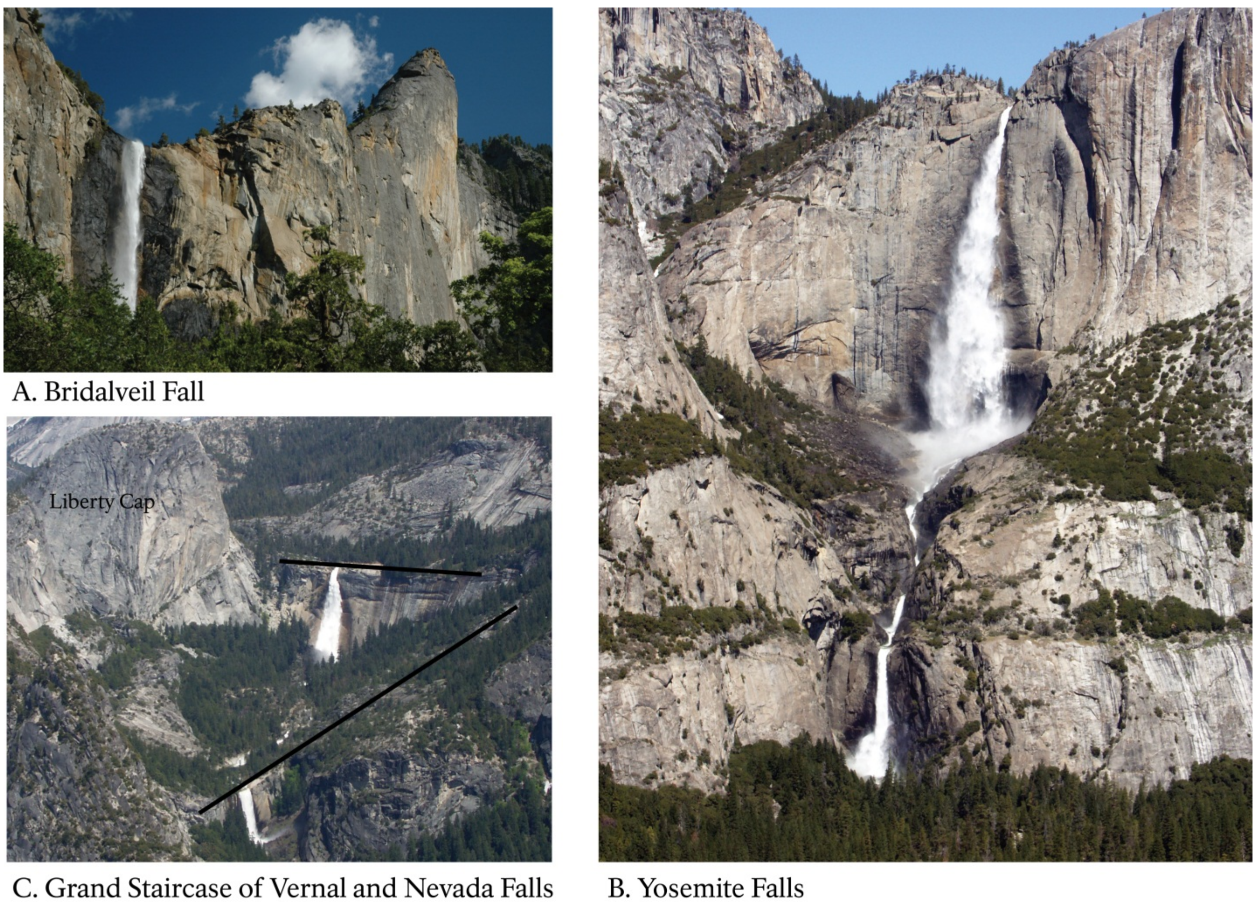


Figure 43. Selected waterfalls in Yosemite National Park. A. Bridalveil Fall. In contrast to the U-shaped valleys carved by glaciers, Bridalveil Creek has cut a deep V-shaped valley, characteristic of fluvial-incised valleys, above the falls. B. Vernal Fall (foreground) and Nevada Fall. The falls cascade over regional joint patterns that form a giant stairway. The cliffs formed by the joints (black lines) are perpendicular to each other. Nevada Fall is flanked by Liberty Cap. C. Yosemite Falls. Yosemite Creek once flowed through the ravine to the left (west) of the falls that is marked by vegetation. Pushed out of its historic channel in the ravine by glacial moraines, Yosemite Creek has not had the time to cut a deep valley like the one above Bridalveil Fall. National Park Service photographs courtesy of Greg Stock (Yosemite NP). Annotation by the author.

With a total vertical drop of 739 m (2,425 ft), Yosemite Falls is one of North America's tallest measured waterfalls (fig. 43B; National Park Service 2011h). It consists of three separate falls: Upper Yosemite Fall [436 m (1,430 feet)], the middle cascades [206 m (675 feet)], and Lower Yosemite Fall [98 m (320 feet)]. Visible throughout much of Yosemite Valley, Yosemite Falls is the most prominent waterfall in the valley. Upper Yosemite, Sentinel, and Ribbon falls are the only three falls cascading over the rim of Yosemite Valley. Approximately 100,000 years ago, glacial moraines left by various glacial cycles diverted Yosemite Creek from its channel in the ravine west of the falls to its present position, which takes it over the rim of the valley (Glazner and Stock 2010).

Nevada and Vernal falls cascade over jointed bedrock in a stair-step fashion (fig. 43C). These falls were created when glacial ice moved down valley, plucking away closely jointed bedrock between sections of massive granite and sculpting a giant glacial staircase (Matthes 1930). Today, the Merced River drops 181 m (594 ft) over Nevada Fall to Emerald Pool and then Vernal Fall, which drops 97 m (317 ft) into Yosemite Valley.

The orientation of these cliffs reflects regional joint patterns. Nevada Fall plunges over a northeast-trending cliff that parallels such features as the face of Half Dome, the notch between Liberty Cap and Mt. Broderick, and Tenaya Canyon. This regional joint pattern is oriented about 90° from the northwest-trending face of Vernal Fall (Calkins et al. 1985). The cliff at Vernal Fall coincides with the regional joint pattern that borders Glacier and Washburn points, North Dome, and the joints around Taft Point.

Recent Geomorphic Features

Fluvial Features

Rivers and streams modified the topography of Yosemite National Park before glaciers were present, and they continue to shape the landscape today. Tuolumne and Merced rivers, which drain all of Yosemite National Park, are designated as Wild and Scenic Rivers and exhibit a plethora of fluvial features (fig. 44).

The high peaks of the park's eastern and northern borders define the drainage basin of the Tuolumne River, which is sourced by meltwater from the Lyell and Maclure glaciers. The Tuolumne meanders through Tuolumne Meadows before flowing through wilderness canyons to the Hetch Hetchy Reservoir. Bounded by steep canyon walls, the river's channel continues to vertically incise granitic bedrock.

Tributary streams flowing from the high peaks along the park's southeastern boundary coalesce to form the main stem of the Merced River. The river meanders through Little Yosemite Canyon before cascading over Nevada and Vernal falls and flowing into Yosemite Valley.

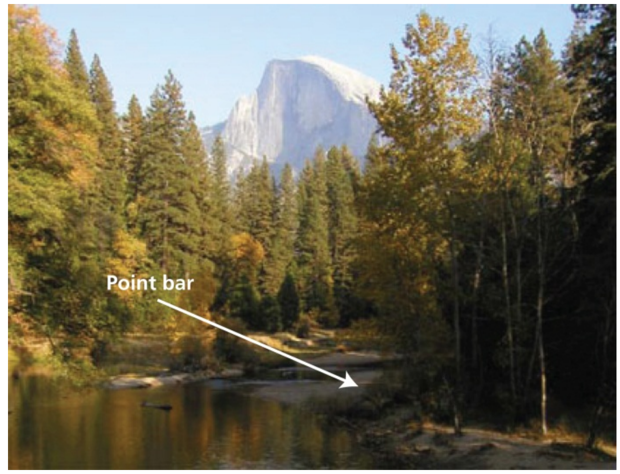


Figure 44. The Merced River flows around a point bar formed in a meander bend in Yosemite Valley. National Park Service photograph.

Meandering through wide, glacially-cut U-shaped valleys, these rivers and their tributaries construct point bars, cutbanks, floodplains, and terraces. In a meandering stream, the maximum velocity of the main current migrates from bank to bank. Point bars form on the inside of a meander curve as the current wanes and sediment drops out of suspension. The current increases on the outside of the bend, laterally eroding the bank to form a cutbank. In this way, meandering streams migrate laterally across valley floors. Floods spread sediment on the rivers' floodplains. Should a river's gradient increase, its channel may incise and begin to erode a new floodplain, leaving the old one as a terrace.

Although generally low in comparison with other rivers, sediment load in Yosemite's streams and rivers change seasonally. Most precipitation accumulates as snow during winter. When the snow melts, high-velocity and turbulent flow increases in the streams as does the capacity of these systems to carry sediment and debris. Flooding may occur, depositing material in floodplains (see the Geologic Issues section). By late summer and autumn, stream flow has decreased and many waterfalls have become dry. The dynamic interaction between stream flow and sediment load in high mountain streams continues to be an active field of research for fluvial geomorphologists.

Mountain streams do not have a smooth profile. Changes in gradient, or slope, occur due to a variety of reasons, including rockfalls that may constrict a stream's channel, tectonic uplift of the Sierra Nevada, and preferential erosion of softer bedrock. For example, when the Merced River down-cut through the El Capitan moraine, its relatively flat, upstream gradient increased and a small rapid formed (Smillie et al. 1995). Prominent changes in river gradients are called knickpoints. Hanging waterfalls are the most extreme examples of knickpoints in Yosemite National Park.

A river is in a constant state of dynamic equilibrium that acts continually to smooth out knickpoints or perturbations in its profile. Because erosion is focused at knickpoints, they tend to migrate upstream, although at extremely slow rates rarely measurable within a human life span.

In March and April, frazil ice forms on Yosemite Creek below Upper and Lower Yosemite falls from frozen crystals of mist (fig. 45). As the ice accumulates and flows downstream, the crystals coalesce into a thick, slushy slurry that may surge in one place and stop, forming a temporary levee that changes the direction of Yosemite Creek's flow (National Park Service 2010c). When the water drains away, the frazil ice looks like snow, but it remains soft and unconsolidated. Frazil ice contributes to flooding and may impact visitor safety (see the Geologic Issues section).

Figure 45. Frazil ice forms a slurry on Yosemite Creek. National Park Service photograph.

Every winter, a conical mound of ice and snow forms at the base of Upper Yosemite Fall (fig. 46). This snow cone may be 30–60 m (100–200 ft) high, and heights exceeding 90 m (300 ft) have been recorded (Glazner and Stock 2010). It develops from the freezing of water at the base of the waterfall and from the separation of ice from the cliff ice upon exposure to the morning sun. These falling sheets of ice can be heard throughout Yosemite Valley (National Park Service 2010c).

The frazil ice in Yosemite Valley is not simply comprised of washed out snow cone remnants. As temperatures warm, the snow cone gradually melts and flow in Yosemite Creek increases. However, persisting nightly subfreezing temperatures freeze some of the creek's flow. In this way, the snow cone is only indirectly related to frazil ice formation. Frazil ice is also observed in locations not associated with a snow cone, such as Royal Arches Cascade, Ribbon Creek, Bridalveil Falls, and Salmon Creek (National Park Service 2010c).

Other Weathering and Erosional Features

Flowing water, glacial ice, and gravity are the primary erosional processes responsible for the present landscape in Yosemite National Park. However, other, more subtle agents of erosion and weathering continue to wear down the park's granitic bedrock.

Along Cherry Lake Road, light-colored, large, rounded boulders of granite are embedded in reddish laterite soil (fig. 47A). Such soils typically form in hot, wet, tropical climates where intense chemical weathering has dissolved most minerals, including quartz, leaving behind an insoluble mass of iron oxides, which provide the rusty red color, and aluminum hydroxides. This soil documents a tropical climate in the Eocene (55–34 million years ago), when tropical forests extended as far as latitude 45° north, the latitude of Maine, and temperate forests (like those in the park today) reached the poles (Glazner and Stock 2010). Easily eroded by glaciers, red laterite soils are currently exposed only in areas of the Sierra that were not glaciated.

Seemingly incongruous with the red soil, the light-colored boulders, called core-stones, actually originated from the same granite. Their rounded shape is a result of weathering processes, rather than transportation by water or ice (fig. 47B). Like exposed bedrock today, the granitic bedrock millions of years ago contained joints and cracks in which groundwater and organic decay products circulated. Rapid weathering occurred along joint edges and corners, rounding them. The minerals in the granite disaggregated, forming a granitic sand called grus that eventually surrounded the core of the granitic block. In the tropical climate, weathering transformed grus into laterite soil (Huber 1989; Glazner and Stock 2010).

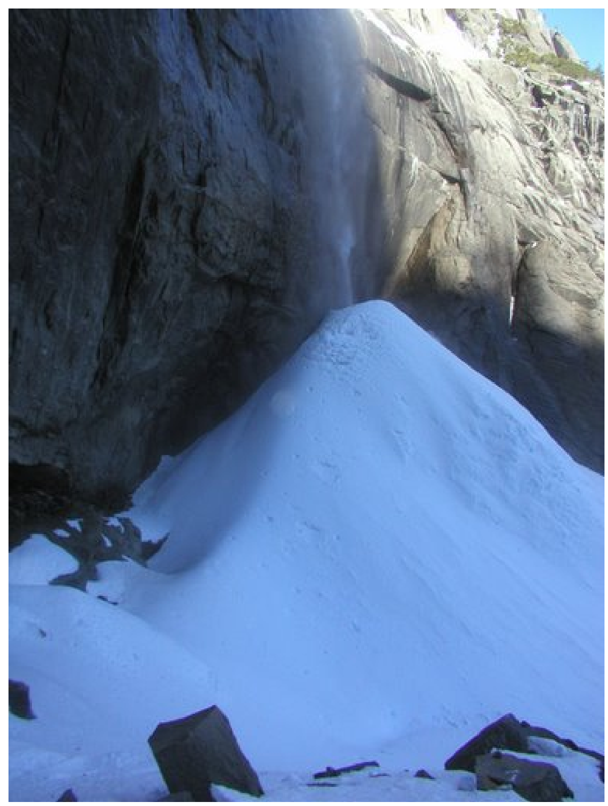


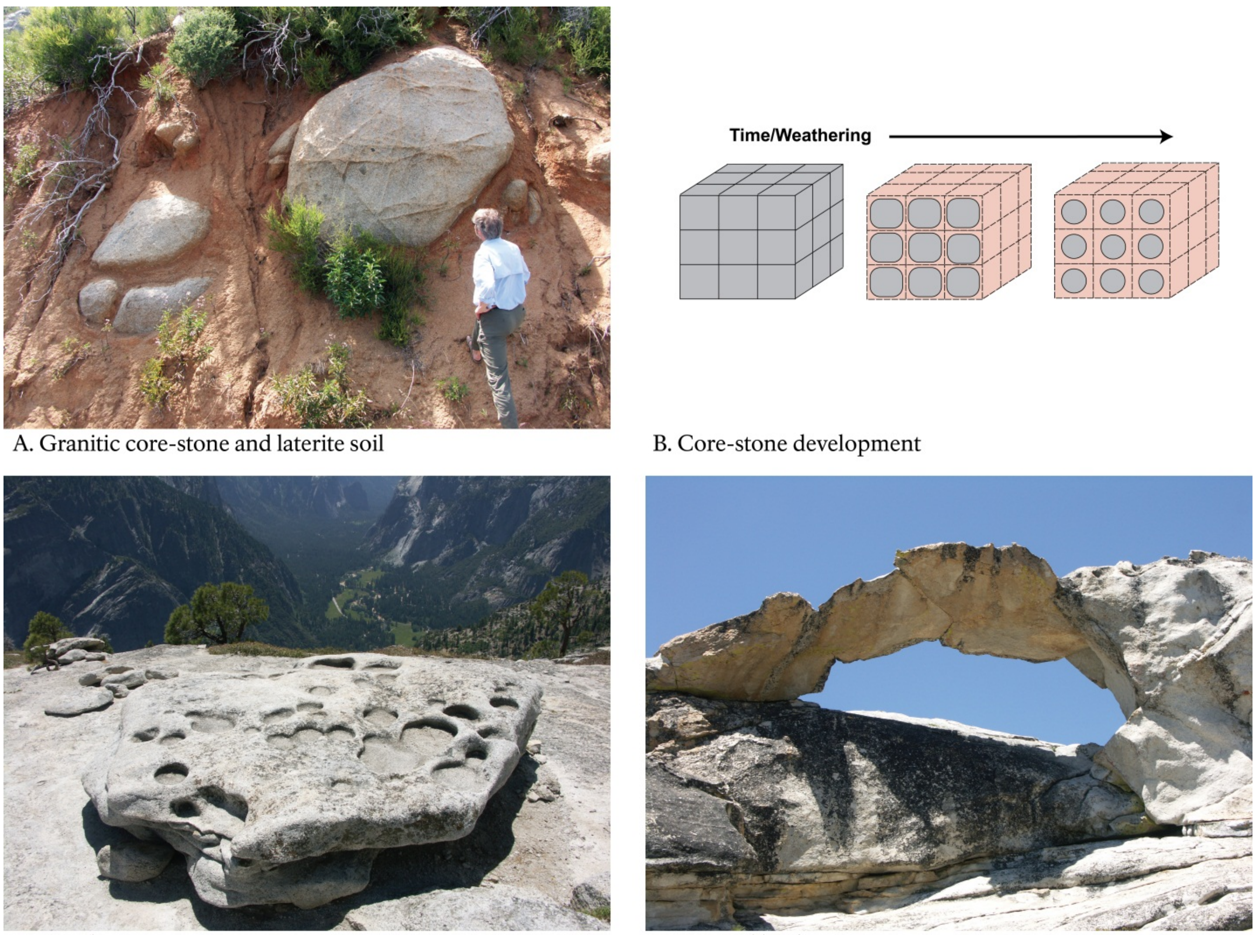
Figure 46. A large snow cone forms at the base of Upper Yosemite Fall. National Park Service photograph courtesy of Greg Stock (Yosemite NP).

Once erosion removes the surrounding soil, core-stones may remain as isolated boulders resting on bedrock. Boulders and bedrock may consist of the same rock type. Not surprisingly, core-stones are commonly misinterpreted as glacial erratics. For example, the isolated boulders in the Tamarack Flat Campground area are core-stones; although they look like glacial erratics, this area has never been glaciated (Glazner and Stock 2010).

Water may also collect in natural depressions on rock surfaces and chemical weathering may enlarge these depressions to form pits, or pans (fig. 47C). These weathering pans are commonly flat-bottomed and may have overhanging rims. Wind may remove weathered material remaining in the pans after the water evaporates, although sand-sized pieces of granite remain in some deeper pits. The pits require a long time to form and are not found on surfaces scraped smooth by the last major glaciation (Huber 1989).

The composition and texture of Yosemite's granitic rocks also play a part in bedrock weathering and disintegration. Granitic rocks that contain abundant biotite weather more rapidly than lighter-colored rocks with little biotite. Biotite absorbs water into its sheet-like crystalline structure and expands, thereby freeing biotite crystals from surrounding mineral grains.

Coarser-grained rocks containing biotite weather more rapidly than finer-grained rocks. Differential erosion and weathering have produced some unusual features in Yosemite National Park, such as knobs of resistant diorite in El Capitan Granite and natural bridges composed of finer-grained material relative to the surrounding bedrock (fig. 47D).



A. Granitic core-stone and laterite soil

B. Core-stone development

C. Weathering pans

D. Natural bridge

Figure 47. Modern weathering and erosion features, Yosemite National Park. A. Light-colored granite core-stones within red laterite soil in a roadcut along Cherry Lake Road. The boulders and soil derived from the same granite. B. Formation of core-stones. Weathering along joints rounds the edges of joint-bounded blocks. Eventually, the core-stones (gray) are left surrounded by a matrix of weathered, oxidized granite called grus. In a tropical climate, grus develops into a laterite soil. Erosion may remove the soil and leave the core-stone isolated on bedrock, resembling a glacial erratic. C. Weathering pans on the summit of North Dome. As weathering continues, the pans may coalesce. Pans are usually flat-bottomed and may have overhanging rims. D. Erosion of less-resistant Half Dome Granodiorite (map unit Khd) beneath a weather-resistant aplite dike opened this natural bridge, called Indian Rock Arch. National Park Service photographs courtesy of Greg Stock (Yosemite NP).

Geologic History

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

The massive granite of the Sierra Nevada and the imposing landscape carved by glaciers allow the geologic story of Yosemite National Park to be considered in two distinct parts: 1) the deposition and deformation of metamorphic rocks and emplacement of granitic rocks during the Paleozoic and Mesozoic, and 2) uplift, erosion, and glaciation during the Cenozoic that produced the modern landscape. Significant chapters in this geologic story include the assembly of California, the intrusion of the Sierra Nevada Batholith, ancient volcanoes, the formation of the San Andreas Fault, uplift of the Sierra Nevada, and carving by ice. In addition to this brief summary, interpreters may find excellent information about the geologic history of Yosemite in Glazner and Stock (2010) and Dunham and Lillie (2009).

The modern Sierra Nevada is a relatively young mountain range. Plutons coalesced into the Sierra Nevada Batholith during the Cretaceous period about 100 million years ago, which represents only about 2% of Earth's history. However, the uplift and exposure of the granitic rocks did not occur until much more recently, at most about 16 million years ago.

The emplacement of the batholith, along with the complex folding and faulting associated with the active tectonic western margin of ancestral North America, destroyed most of the earlier geologic record of central California. Rocks in the western metamorphic belt offer some clues to the Paleozoic and Mesozoic history of central California, but most evidence lies east and west of the Sierra Nevada. Using isotopic and relative age-dating techniques, subsurface geophysical and well data, and analysis of surface exposures 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. Some of the geologic history can be interpreted in considerable detail, whereas other pages of the geologic record remain blank due to a lack of data.

Assembling California: The Paleozoic Era (542–251 million years ago)

Approximately 500 million years ago, most of what is now California lay submerged to the west of the emerging North American continent (fig. 48). The western margin of North America was a passive margin similar to the East Coast of North America today. Paleogeographic maps (such as fig. 48) locate the region of today's Yosemite National Park far to the west of the Cambrian shoreline. This coast would not have supported vegetation, which did not exist in the Cambrian.

The sand deposited in Cambrian near-shore environments became the Tapeats Sandstone in Grand Canyon National Park and the Zabriskie Quartzite in Death Valley National Park (Middleton and Elliott 1990; Martin and Walker 1991; Mount et al. 1991; Glazner and Stock 2010). Mud, silt, and shell fragments drifted into the deep-marine continental shelf environment of the land now containing Yosemite National Park and eventually solidified into shale, siltstone, and carbonate rocks (Stewart 1991). This traditionally accepted scenario, however, does not explain the presence of Cambrian-aged beach sand (metamorphosed to quartzite) at May Lake in Yosemite National Park (see the May Lake Quartzite subsection of the Geologic Features section).

By the end of the Ordovician, the tectonic setting changed from passive to active as an oceanic plate began descending (subducting) beneath the continent. A deep trench formed in association with the subduction zone. The jumbled assemblage of rocks and debris that accumulated in the trench has been mapped in the southwestern corner of the park as part of the Shoo Fly Complex (map units PZpsq, PZps, and PZpr), which includes marine sedimentary rocks (limestone and chert), igneous rocks (gabbro and basalt), volcaniclastic rocks, and terrestrially-derived sediments (clay, silt, and sand) (McMath 1966; Harwood 1992; Miller et al. 1992). Many of the terrestrially-derived sediments in the Shoo Fly Complex were eroded from Precambrian igneous rocks exposed in northwestern North America (Miller et al. 1992; Girty and Lawrence 2000; Harding et al. 2000). Volcanic material was deposited from volcanic islands erupting to the west of the trench (fig. 48; Harding et al. 2000).

From the late Early Silurian through the Late Devonian (430–359 million years ago), tectonic collision compressed the Shoo Fly Complex against the western margin of ancestral North America. The unit was folded and stacked into at least four packages of strata separated by regional thrust faults (fig. 49; Harwood 1983, 1992; Girty et al. 1991; Miller et al. 1992).

The California coast continued to be an active subduction zone from the Late Devonian through the Early Mississippian (385–345 million years ago) (Dickinson 1977; Poole and Sandberg 1977; Johnson et al. 1991). The continued collisions accreted additional material, such as the Sullivan Creek Terrane, onto the western margin of North America, and built mountains in Nevada and Idaho. South America began colliding

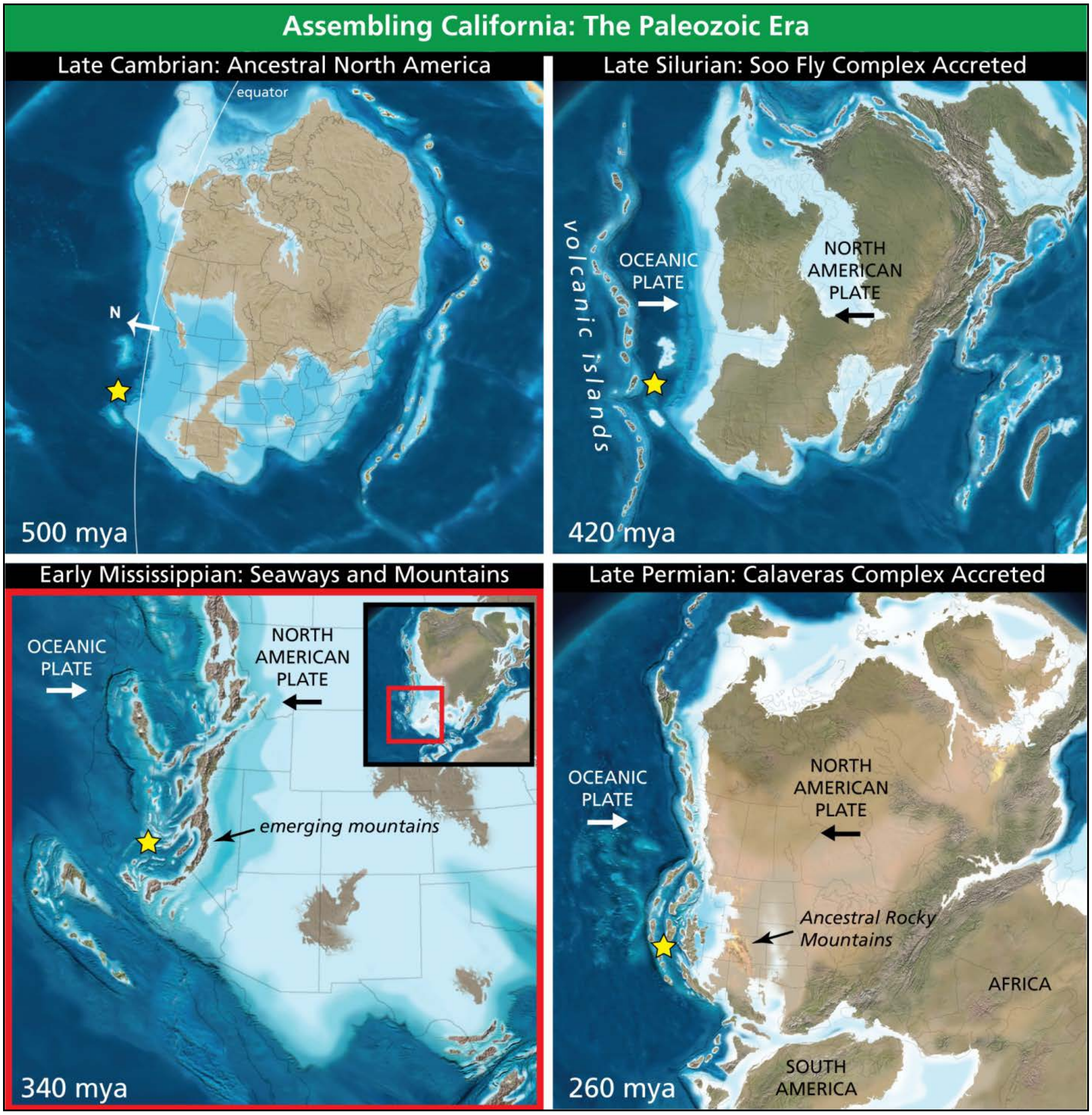


Figure 48. Paleozoic paleogeographic maps of North America. In the Late Cambrian, approximately 500 million years ago (mya), the Sierra Nevada region and future site of Yosemite National Park (yellow star) lay offshore of the passive western margin of the emerging North America continent. By the Late Silurian, approximately 420 million years ago, the passive margin had become an active tectonic margin, and the approaching subduction zone created volcanic islands. The collision of ancestral North America with the oceanic plate compressed and attached the Shoo Fly Complex to the western margin of the continent. In the Early Mississippian, approximately 340 million years ago, a slab of oceanic lithosphere continued to subduct beneath the North American continent. A shallow sea covered large portions of western North America, and mountains emerged in central Nevada and Idaho. By the end of the Permian (251 million years ago), the assembly of Western Pangaea was complete. Subduction of the oceanic plate beneath North America continued along the western margin, accreting the Calaveras Complex to California. South America collided with North America, forming the northwest–southwest-trending Ancestral Rocky Mountains in Colorado. Block arrows indicate the relative directions of plate movement. Base paleogeographic maps by Ron Blakey (Colorado Plateau Geosystems, Inc.), available at http://cpgeosystems.com/paleomaps.html. Annotation by the author and Jason Kenworthy (NPS Geologic Resources Division).

with North America, generating tremendous forces far inland that led to the construction of the Ancestral Rocky Mountains. Relative sea level rose and an expansive sea inundated a large portion of the continent (fig. 48).

The details of the depositional and tectonic history of the Upper Permian–Early Jurassic Calaveras Complex in central California continue to puzzle geologists (fig. 48). The unit consists of detritus from the western continental margin of North America, as well as chaotic blocks of sediments and submarine debris-flow deposits that accumulated on a substrate of pillow lava, tuff-breccia, and tuff associated with a volcanic arc (Wright and Schweickert 1977; Cullers and Schweickert 1999; Van Guilder et al. 2010). Prior to deformation, these units may have been thousands of meters thick (Wright and Schweickert 1977). Fossils in blocks of limestone within the Calaveras Complex suggest that the limestone traveled thousands of kilometers across the ancestral Pacific Ocean before becoming part of this exceptionally complicated sequence of disrupted sedimentary strata (Stevens 1991; Saleeby and Busby-Spera 1992).

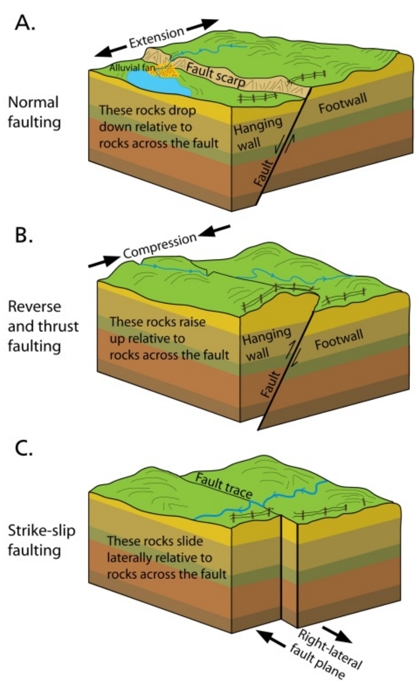


Figure 49. Fault types. In a normal fault (A), the hanging wall moves down relative to the footwall in response to extension (pulling apart) of the crust. In a reverse fault (B), the hanging wall moves up relative to the foot wall in response to compression of the crust. A thrust fault is similar to a reverse fault, but the dip angle is less than 45°. A strike-slip fault (C) results in relative horizontal movement. If the relative direction of movement has been to the right (as in this example), the fault is a right-lateral (dextral) strike-slip fault. If movement is to the left, the fault is a left-lateral (sinistral) strike-slip fault. A strike-slip fault between two plate boundaries is called a transform fault. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Thrust faults (fig. 49) separate the terranes and complexes of rocks that were accreted onto the western edge of North America and now underlie much of California.

Rise of the Batholith: The Mesozoic Era (251–65.5 million years ago)

Plate subduction along the active tectonic margin of western North America continued throughout the Mesozoic and continues today. Subduction generated magma at depth that fed volcanoes on the overriding North American Plate in a manner similar to today's Mount St. Helens and other volcanoes in the Cascade Range (fig. 50). This chain of volcanoes stretched nearly the entire length of the western margin of North America. Volcanic detritus from the volcanic island-arc and clastic sediments eroded from the continent accumulated in the adjacent marine basin (Oldow et al. 1989). Deformation of this diverse assemblage, along with volcanism and pluton development, occurred in the Death Valley and Mojave regions of California during the Late Permian and Early Triassic as all of Earth's major land masses continued to suture together to form the supercontinent Pangaea (Trexler et al. 1991; Dubiel 1994; Dunston et al. 2001).

Triassic and Jurassic Periods (251–146 million years ago)

During the Late Triassic and early-Middle Jurassic, subduction of the oceanic plate thrust the Calaveras Complex eastward beneath the Shoo Fly Complex, attaching it to the western margin of the North American continent (Stevens 1991; Saleeby and Busby-Spera 1992; Van Guilder et al. 2010). In the western metamorphic belt that borders Yosemite National Park, the Sonora Fault has been mapped as separating the Calaveras Complex from the older, volcanic-rich Sullivan Creek Terrane. Although it ranges in age from Upper Permian to Early Jurassic, much of the Calaveras Complex is similar in age to the Jurassic Mariposa Formation in this area of the park (Van Guilder et al. 2010).

Significant magma generated beneath the Cordillera in the Middle Jurassic fueled volcanic islands west or southwest of North America's western margin (Hamilton 1978; Schweickert 1978; Oldow et al. 1989). During the Late Jurassic, these volcanic islands accreted to the North American continent.

The deep-marine sediments in the Mariposa Formation (map unit Jmaf) accumulated in a basin between the volcanic islands and North America (fig. 50) during the Upper Jurassic (Snow and Ernst 2008; Ernst et al. 2009). Clastic sediments were derived from the Klamath Mountains, continental sources to the east, and an active volcanic arc. Late in the Upper Jurassic (about 150–140 million years ago), the Mariposa Formation was deformed by oblique, left-lateral convergence of the Farallon Plate relative to North America (fig. 50), displacing the Klamath region by approximately 200 km (124 mi) (Ernst et al. 2009). Refer to figure 49 for more information about fault types and terminology.

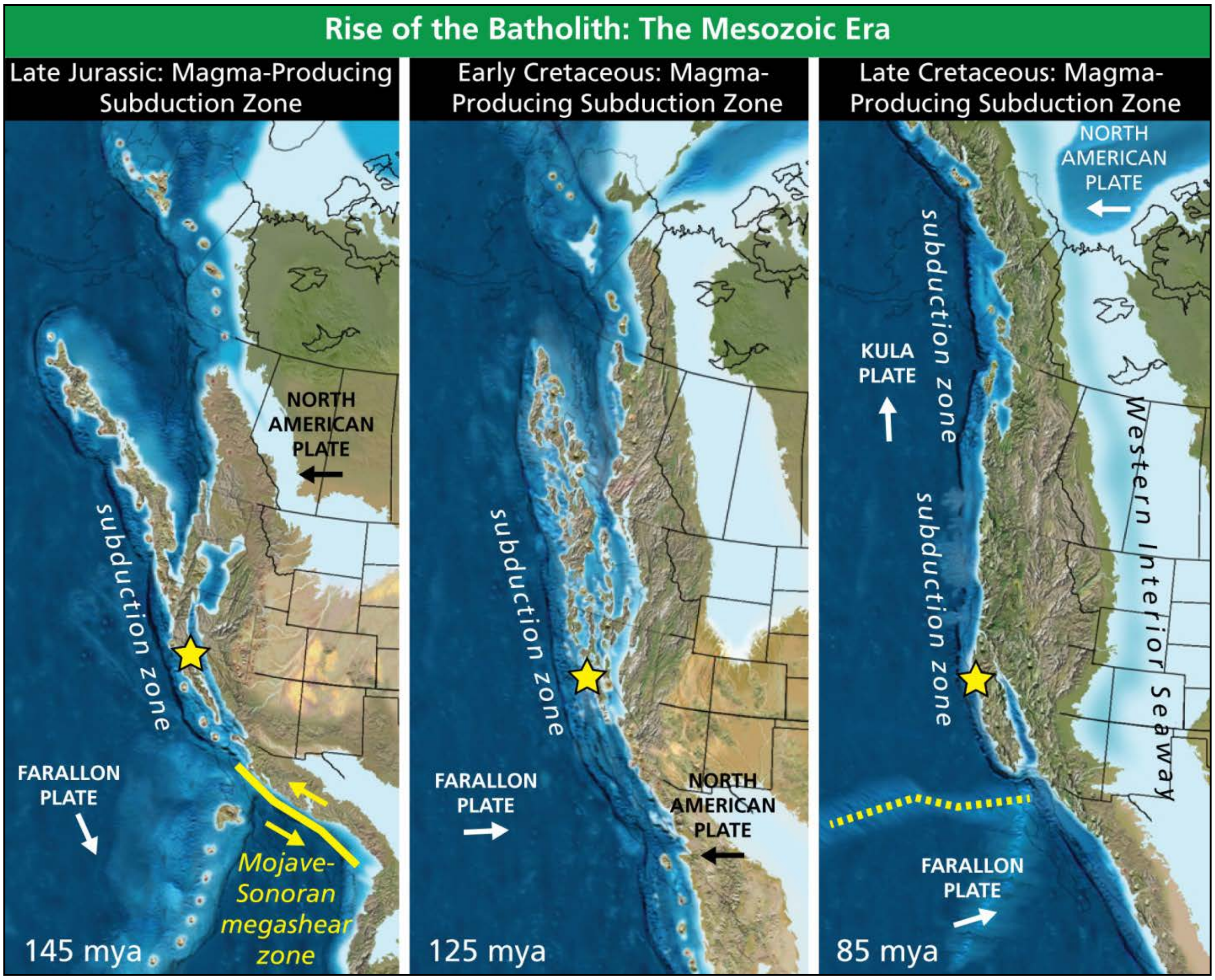


Figure 50. Mesozoic paleogeographic maps of North America. In the Late Jurassic, approximately 145 million years ago (mya), tectonic plate motion changed so that oblique convergence of the Farallon Plate relative to North America caused left-lateral displacement along the western continental margin. The large Mojave-Sonoran megashear zone (yellow line) developed along the southwestern margin. By the Early Cretaceous, approximately125 million years ago, the subduction zone had reorganized to become parallel to the western margin of North America. Head-on collision between the North American and Farallon plates produced magma at depth and the beginnings of a fold-and-thrust belt in Nevada, Utah, Idaho, and Wyoming. In the Late Cretaceous, approximately 85 million years ago, the Sierra Nevada Batholith had formed, and the Western Interior Seaway reached its maximum extent. Yellow stars indicate the approximate location of today's Yosemite National Park. Block arrows indicate the relative directions of plate movement. Base paleogeographic maps by Ron Blakey (Colorado Plateau Geosystems, Inc.), available at http://cpgeosystems.com/paleomaps.html. Annotation by the author and Jason Kenworthy (NPS Geologic Resources Division).

Cretaceous Period (145.5–65.5 million years ago)

Transpression (compression with a strike-slip component) in the Early Cretaceous displaced the metamorphic rocks (such as map unit JTRmb) near May Lake up to 400 km (250 mi) northward (Schweickert and Lahren 1991). By approximately 120 million years ago, left-lateral transpression had given way to "head-on" subduction between the Farallon Plate to the west and the North American Plate (fig. 50; Ernst et al. 2009). This tectonic regime change produced the voluminous magma that formed the Sierra Nevada Batholith and emplaced continental-margin plutons from Mexico to the Alaskan peninsula (Oldow et al. 1989; Christiansen et al. 1994; Dubiel 1994; Lawton 1994).

The head-on collision of these two tectonic plates generated intense friction and pressure that generated sufficient heat to melt rocks. The descent of denser oceanic Farallon Plate into the asthenosphere and mantle of the lithosphere generated magma that had the composition of basalt or andesite, dark-colored rocks with little silica. The buoyant magma rose through the silica-rich continental crust, partially melting the overriding lithosphere, and becoming more granitic in composition. About 140–80 million years ago, the granitic magma pooled at depths of only 3–8 km (1.8–4.9 mi) beneath the active volcanoes erupting at the surface (Fiske and Tobisch 1978; Hamilton 1978; Huber 1989; Oldow et al. 1989; Glazner and Stock 2010). Hundreds of distinct plutons, up to 1,000 km^2 (380 mi^2) in size, combined to form the Sierra Nevada Batholith, a composite mass about 100 km (40 mi) wide (Hamilton 1978; Huber 1989). The 10 intrusive suites of Yosemite National Park (fig. 5) are evidence of this activity.

Active volcanoes similar to the modern Cascades erupted above the Sierra Nevada plutons. Voluminous quantities of ash blew eastward as far as Kansas. Ash layers of the same age found in the midcontinent and volcanic deposits in the Central Valley suggest that these Cretaceous volcanoes produced extraordinary amounts of volcanic material (Glazner and Stock 2010). For example, a 4- km (2.5- mi)- thick section of Cretaceous ash-flow tuff in the Ritter Range, southeast of the park, contains caldera-collapse breccia deposits more than 1-km (0.6- mi)- thick (Fiske and Tobisch 1978).

Continued subduction along the west coast of North America produced enormous thrust sheets of rock that formed a north–south-trending fold-and-thrust belt extending from Canada through western Montana, eastern Idaho, southwestern Wyoming, central Utah, and into southeastern Nevada (Lageson and Schmitt 1994; DeCelles 2004). Regional-scale thrust packages thickened the crust in the area is now 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).

As mountains rose along the western margin, rifting between North and South America opened the Gulf of Mexico, and seawater spread northward. Marine water also began to advance 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. 50).

The seaway receded from the continental interior with the onset of the Laramide Orogeny (mountain-building event), which occurred about 35–70 million years ago. This orogeny marked a pronounced eastward shift in tectonic activity as the angle of the subducting slab flattened and compressive forces were felt far inland (fig. 51B). Rather than generating volcanic mountain ranges on the west coast as in previous orogenies, the Laramide Orogeny displaced deeply- buried Precambrian plutonic and metamorphic rocks that are now exposed in the core of the Rocky Mountains.

The much shallower angle of subduction during the Laramide Orogeny prevented rocks from melting, thus eliminating the magmatic source for the ancestral Sierra Nevada. After magma generation ceased, erosion became the dominant force shaping the range, removing the volcanoes above the batholith. By the early Paleogene, approximately 63 million years ago, most older volcanic and metamorphic rocks had been eroded, exposing the granitic core of the ancestral Sierra (Huber 1989; Huber and Eckhardt 2002). Relief on the exposed batholith was only a few thousand feet by the middle of the Cenozoic.

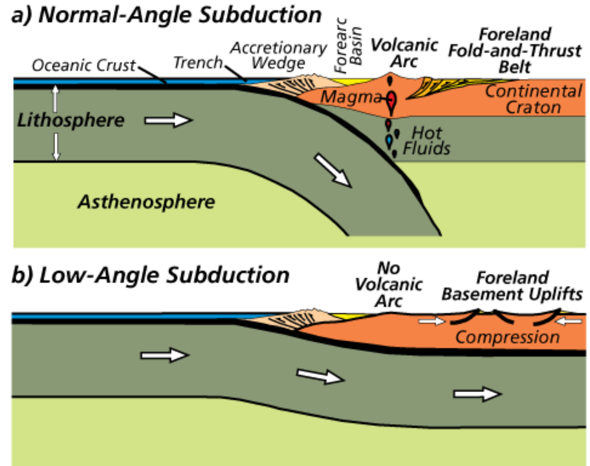


Figure 51. Schematic diagrams of normal-angle and low-angle subduction zones off the western margin of North America during the Mesozoic. A. In a normal plate-tectonic setting, a relatively steep angle of subduction causes melting above the downgoing slab. Magma rises to the surface and erupts, forming a volcanic arc along the continental margin, similar to the present Andes Mountains of South America. A forearc basin forms between the volcanic arc and the trench. Sediments compressed in the trench form an accretionary wedge against the volcanic arc. Sedimentary strata that are folded and thrust toward the continental craton form a foreland fold-and-thrust belt. In the Triassic, oceanic–oceanic plate convergence caused a volcanic arc to form offshore and a backarc oceanic basin to form between the volcanic arc and the continent. During the Jurassic, the oceanic plate collided with the North American continent to form a volcanic arc along the western margin of North America. B. In low-angle subduction, the downgoing slab does not extend deeply enough to generate magma producing heat; volcanism is thus absent or occurs closer to the craton. The subducting slab transmits stress farther inland, causing hard rock in the crust to compress and break along reverse faults to form basement uplifts, such as those that created the Rocky Mountains. During the Late Cretaceous–Tertiary Laramide Orogeny, the low angle of the subducting slab caused deformation to occur farther inland. Diagram from Lillie (2005, fig. 10.29).

Tension, Uplift, and Ice: The Cenozoic Era (65.5 million years ago–present)

Paleogene and Neogene Periods (Tertiary; 65.5–2.6 million years ago)

By about 25–15 million years ago (early Miocene), the portion of the Farallon Plate off the California coast had completely subducted and the Pacific Plate intersected North America (fig. 52). Because the Pacific Plate was moving along-side the North American Plate, rather than subducting beneath it, the San Andreas strike-slip fault activated along this segment of the coast. 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 (and still moving) right-lateral slip of greater than 320 km (200 mi) (Oldow et al. 1989). Many NPS and other public land areas in California are along or near the San Andreas Fault, including Point Reyes National Seashore and Pinnacles National Monument (Stoffer 2006).

The change from subduction to strike-slip movement further removed support for the thick crust that had built

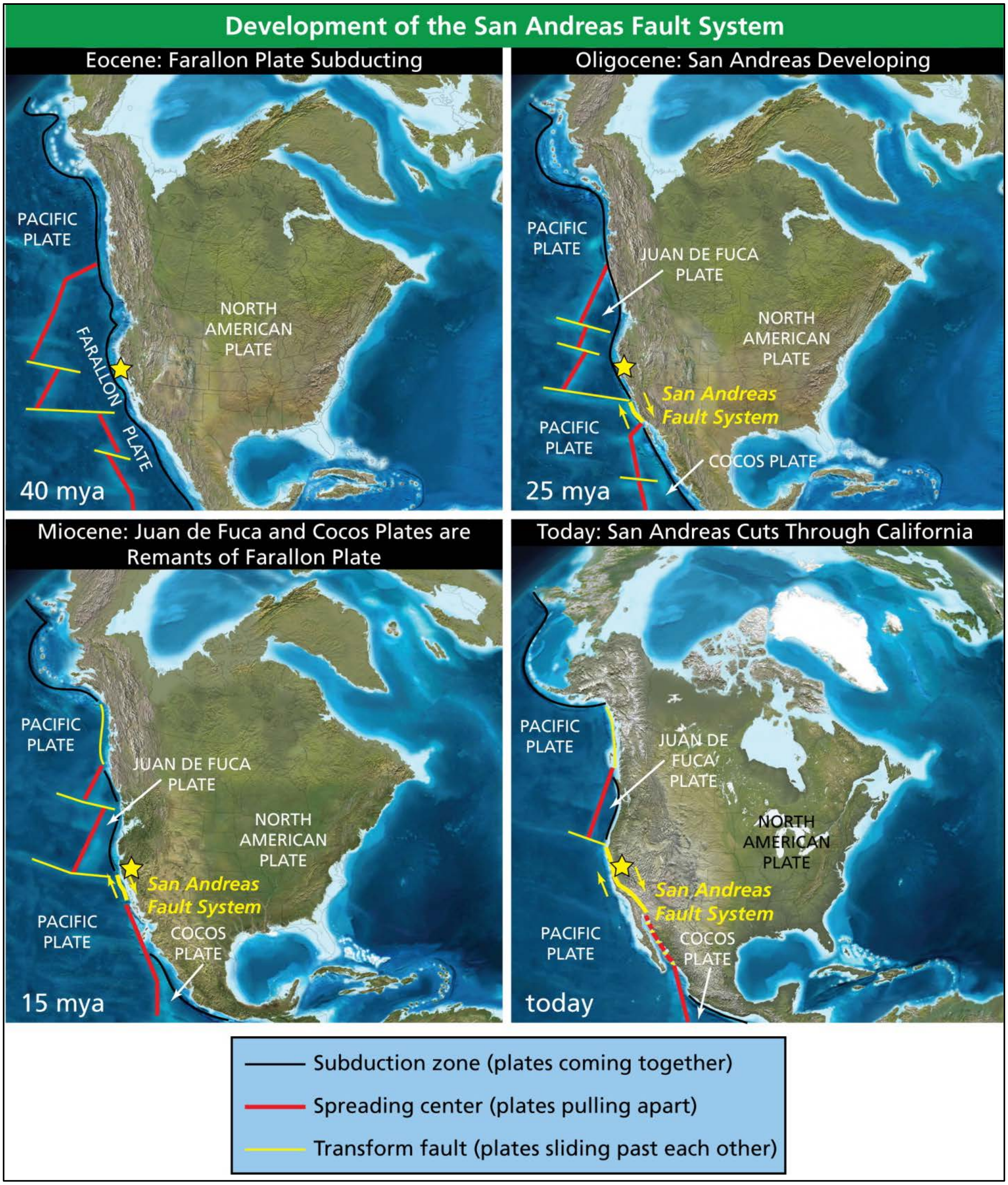


Figure 52. Growth of the San Andreas Fault System. When the spreading center between the Pacific and Farallon plates intersected the North American Plate, a transform fault formed (San Andreas Fault zone), causing strike-slip (transpressional) movement. The Farallon Plate has been subdivided into the Juan de Fuca Plate, to the north, and the Cocos Plate, to the south. Yellow stars indicate the approximate location of today's Yosemite National Park. "mya" = million years ago. Base paleogeographic maps by Ron Blakey (Colorado Plateau Geosystems, Inc.), available at http://cpgeosystems.com/paleomaps.html. Annotation by the author and Jason Kenworthy (NPS Geologic Resources Division).

up 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 1989; Park et al. 1996). U.S. Route 395 east of Yosemite National Park roughly parallels the fault boundary between the Basin and Range and the Sierra Nevada.

Coincident with the origin of the San Andreas Fault system to the south, volcanic activity returned to the northern Sierra Nevada (Huber 1989; Glazner and Stock 2010). Within Yosemite National Park, remnants of this fiery episode can be found in the approximately 9.4 million-year-old (Miocene) basaltic rocks of the Little Devils Postpile (map unit Tbo; fig. 21; Bateman et al. 1983). Most of the volcanic rocks, however, are in the northern Sierra Nevada, and east and southeast of the park near Mono Craters and Devils Postpile National Monument (Huber et al. 1989; Graham 2009).

Considerable debate and research continues with regard to the timing of the Sierra Nevada's development as a mountain range. Isotopic composition of in-situ clay minerals suggests that the Sierra Nevada existed as a major topographic feature throughout much of the Cenozoic (Chamberlain and Poage 2000; Chamberlain et al. 2002, 2005; Mulch et al. 2005, 2006; Cassel et al. 2009). In this view, most of the topography was established in the Paleogene and little change in elevation occurred over the past 16 million years.

River incision rates and cosmogenic dating of cave sediments, however, suggest that a late Cenozoic uplift gave rise to the present elevation of the Sierra Nevada (Stock et al. 2004, 2005). In this view, rapid river incision of approximately 0.2 mm/year (0.008 in/year) 2.7–1.5 million years ago supports a tectonically driven, late Pliocene–Pleistocene uplift. Recent uplift may be superimposed on substantial pre-existing topography (Greg Stock, Geologist and Resource Manager, Yosemite National Park, written communication April 4, 2012).

Quaternary Period (2.6 million years–present)

Regardless of when the modern Sierra Nevada was uplifted, the landscape was greatly altered by glacial ice during the Pleistocene ice ages (table 4). Evidence of glaciation on McGee Mountain suggests that the earliest glacial advance in the Sierra Nevada may have occurred about 1.5 million years ago (Glazner and Stock 2010). The McGee Glaciation was followed by the Sherwin Glaciation about 800,000 years ago. Although considered to be the largest glaciation in the Sierra Nevada, most evidence of the Sherwin Glaciation in Yosemite National Park was removed by subsequent glaciations. A massive erratic on Turtleback Dome near the western edge of Yosemite Valley may be one of the few remaining deposits from this glaciation in the park (Glazner and Stock 2010).

Outside of the park, however, deposits of Sherwin Till have been found beneath (meaning they are older than) the 760,000-year-old Bishop Tuff that erupted from the Long Valley Caldera. Volcanic ash from this catastrophic eruption drifted as far east as Nebraska (U.S. Geological Survey 2007).

Named for deposits near Lake Tahoe, the Tahoe Glaciation covered the Yosemite landscape approximately 140,000–80,000 years ago. It was not as widespread as the Sherwin Glaciation, but it was more extensive then the subsequent Tioga Glaciation. Lateral moraines from the Tahoe Glaciation rise above moraines from the Tioga Glaciation in Lee Vining Canyon, east of the park (fig. 39).

Volcanic activity returned to the region near the end of the Tahoe Glaciation. The vertical columnar basalt in Devils Postpile National Monument, southeast of Yosemite National Park, resulted from volcanic eruptions less than 100,000 years ago. Although present in other parts of the Sierra Nevada, these younger volcanic rocks are not exposed in Yosemite National Park (Huber et al. 1989).

The most recent glaciation in the Sierra Nevada was the Tioga Glaciation, which was named for glacial deposits near Tioga Pass. During a prolonged cold period about 26,000–18,000 years ago, a vast ice field formed in the Tuolumne Meadows area (fig. 53). The majority of glacial features in Yosemite National Park are remnants of the Tioga Glaciation.

When the Tioga ice melted from Yosemite Valley, it left the El Capitan and Bridalveil moraines. Cosmogenic age-dating indicates that the boulders of Cathedral Peak Granodiorite were deposited on the El Capitan moraine about 19,000 years ago (Glazner and Stock 2010).

Within the first 6,000 years of the Holocene (11,000 years ago to present), warming temperatures melted the glaciers in the Sierra Nevada. Fluctuating temperatures over the last 5,000 years have resulted in three relatively small modern glaciations in the Sierra Nevada. The Little Ice Age, a short-lived cooling period between 1350 C.E. and 1850 C.E., initiated the Matthes Glaciation about 500 years ago, which reached its maximum between 1700 C.E. and 1750 C.E. (Huber 1989; Raub et al. 2006; Glazner and Stock 2010).

During the 20th century, glacier retreat in the Sierra Nevada can be grouped into four periods. Glacial area did not change considerably from 1903 to about 1920, but glaciers retreated rapidly from 1920 through the 1960s. Glaciers stopped retreating between the 1970s and early 1980s. Finally, glaciers began retreating again in the late 1980s and melting increased in the early 2000s (Basagic and Fountain 2011).

Active faulting along the eastern border continues to uplift the Sierra Nevada, and modern glaciers in these mountains continue to melt. Westward-flowing rivers carry sediments into the Central Valley. To the east, the

Mono Craters and Inyo domes remain active, with episodic eruptions occurring every few thousand years. Rockfalls continue to alter the granitic landscape of Yosemite National Park.

Today, as so eloquently described by John Muir, explorers of Yosemite National Park experience a landscape that took hundreds of millions of years to construct and hundreds of thousands of years of glaciation to shape.

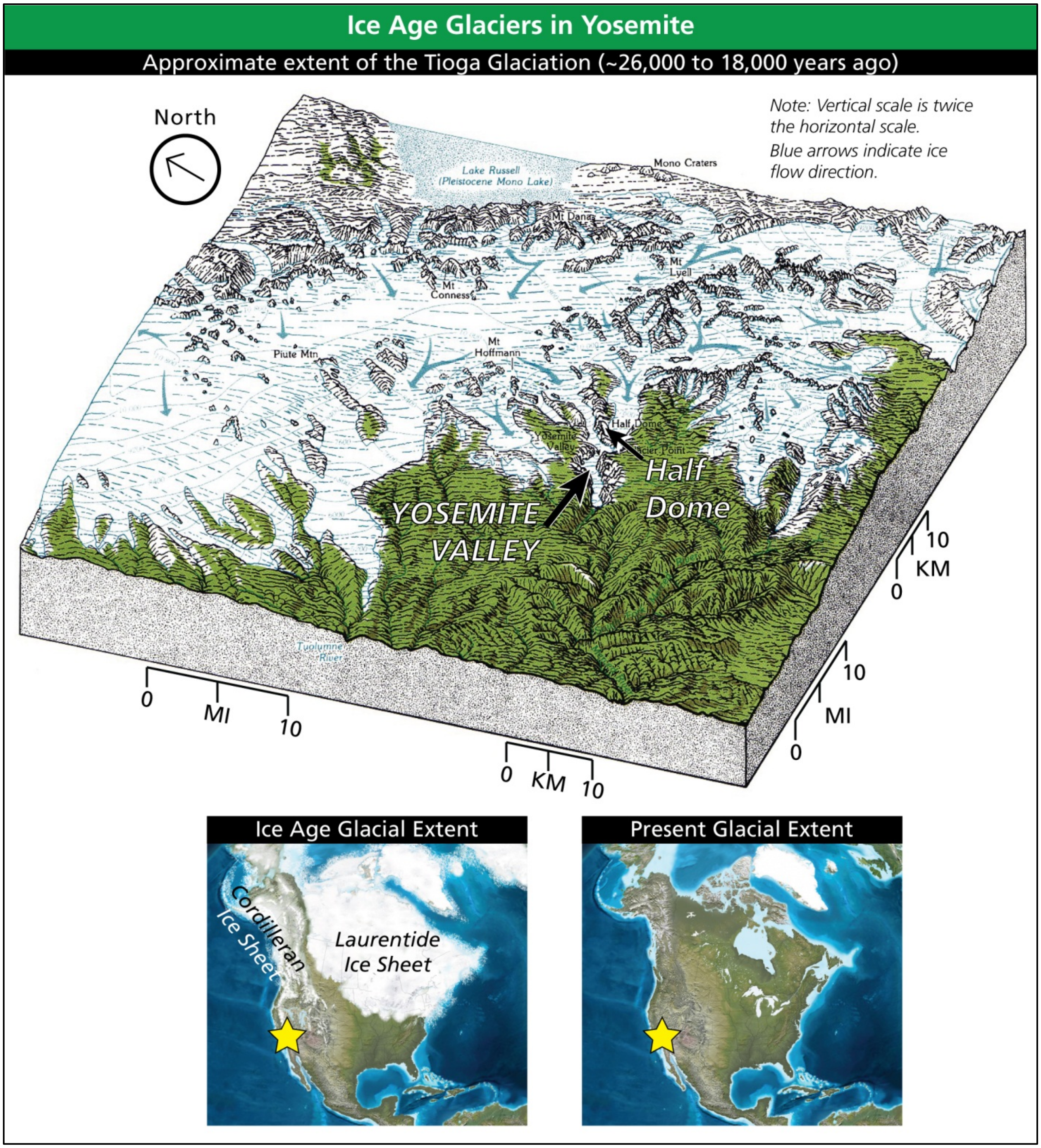


Figure 53. Sketch showing the maximum extent of Tioga glaciation. The nearly 610-m (2,000-ft)- thick ice field formed in the Tuolumne Meadows region and flowed into adjacent valleys, smoothing the landscape. Isolated peaks and ridges jutting above the ice, such as Mt. Hoffman and Half Dome, are nunataks (see the Features and Processes section). Sketch is figure 67 from Huber (1989), available at http://www.yosemite.ca.us/library/geologic_story_of_yosemite/. (accessed February 16, 2011). Yellow stars indicate the approximate location of today's Yosemite National Park. Base paleogeographic maps by Ron Blakey (Colorado Plateau Geosystems, Inc.), available at http://cpgeosystems.com/paleomaps.html. Annotation by the author and Jason Kenworthy (NPS Geologic Resources Division).

Geologic Map Data

This section summarizes the geologic map data available for Yosemite National Park. The Geologic Map Overview Graphics display the geologic map data draped over a shaded relief image of the park and surrounding area. The foldout Map Unit Properties Tables summarize this report's content for each geologic map unit. Complete GIS data are included on the accompanying DVD and are also available at the GRI publications website (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, geologic maps portray the spatial distribution and relationships of rocks and unconsolidated deposits. There are two primary types of geologic maps: surficial and bedrock. Surficial geologic maps encompass deposits that are frequently unconsolidated and formed during the past 2.6 million years (the Quaternary Period). Surficial map units are differentiated by geologic process or depositional environment. Bedrock geologic maps encompass older, generally more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type. For reference, a geologic time scale is included as figure 5. Bedrock and surficial geologic map data are provided for Yosemite National Park.

Geologic maps also may show geomorphic features, structural interpretations, and locations of past geologic hazards that may be prone to future activity. Additionally, anthropogenic features such as mines and quarries may be indicated on geologic maps.

Source Maps

The Geologic Resources Inventory (GRI) team converts digital and/or paper source maps into GIS formats that conform to the GRI GIS data model. The GRI digital geologic map product also includes essential elements of the source maps, including unit descriptions, map legend, map notes, references, and figures. The GRI team used the following source maps to produce the digital geologic data for Yosemite National Park.

Compiled Bedrock and Surficial Data (Entire Park)

Bateman, P.C. 1989. Geologic map of the Bass Lake Quadrangle, west-central Sierra Nevada, California. U.S. Geological Survey Geologic quadrangle GQ-1656 (scale 1:62,500).

Bateman, P.C., and K.B. Krauskopf. 1987. Geologic map of the El Portal quadrangle, west-central Sierra Nevada, California. U.S. Geological Survey Miscellaneous Field Studies MF-1998 (scale 1:62,500).

Bateman, P.C., R.W. Kistler, D.L. Peck, and A. Busacca. 1983. Geologic map of the Tuolumne Meadows quadrangle; Yosemite National Park, California. U.S. Geological Survey Geologic Quadrangle GQ-1570 (scale 1:62,500).

Bateman, P.C., J.P. Lockwood, and P.A. Lydon. 1971. Geologic map of the Kaiser Peak quadrangle, central Sierra Nevada, California. U.S .Geological Survey Geologic Quadrangle GQ-894 (scale 1:62,500).

Chesterman, C.W. 1975. Geology of the Matterhorn Peak quadrangle, Mono and Tuolumne Counties, California. California Division of Mines and Geology, Map Sheet 22 (scale 1:48,000).

Dodge, F.C.W., and L.C. Calk. 1987. Geologic map of the Lake Eleanor quadrangle, central Sierra Nevada, California. U.S. Geological Survey Geologic Quadrangle GQ-1639 (scale 1:62,500).

Huber, N.K. 1968. Geologic map of the Shuteye Peak quadrangle, Sierra Nevada, California. U.S. Geological Survey Geologic Quadrangle GQ-728 (scale 1:62,500).

Huber, N.K. 1983. Preliminary geologic map of the Dardanelles Cone quadrangle, central Sierra Nevada, California. U.S. Geological Survey Miscellaneous Field Studies MF-1436 (scale 1:62,500).

Huber, N.K. 1983. Preliminary geologic map of the Pinecrest quadrangle, central Sierra Nevada, California. U.S. Geological Survey Miscellaneous Field Studies MF-1437 (scale 1:62,500).

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

Kistler, R.W. 1966. Geologic map of the Mono Craters quadrangle, Mono and Tuolumne Counties, California. U.S. Geological Survey Geologic Quadrangle Map GQ-462 (scale 1:62,500).

Kistler, R.W. 1973. Geologic map of the Hetch Hetchy Reservoir quadrangle, Yosemite National Park, California. U.S. Geological Survey Geologic Quadrangle GQ-1112 (scale 1:62,500).

Krauskopf, K.B. 1985. Geologic map of the Mariposa quadrangle, Mariposa and Madera Counties, California. U.S. Geological Survey Geologic Quadrangle GQ-1586 (scale 1:62,500).

Peck, D.L. 1980. Geologic map of the Merced Peak quadrangle, central Sierra Nevada, California. U.S. Geological Survey Geologic Quadrangle GQ-1531 (scale 1:62,500).

Peck, D. L. 2002. Geologic map of the Yosemite quadrangle, central Sierra Nevada, California. U.S. Geological Survey Miscellaneous Investigation I-2751 (scale 1:62,500).

Wahrhaftig, C. 2000. Geologic map of the Tower Peak quadrangle, central Sierra Nevada, California. U.S. Geological Survey Miscellaneous Investigation I-2697 (scale 1:62,500).

Glacial and Postglacial Deposits of Yosemite Valley

Matthes, F.E. 1930. Geologic history of the Yosemite Valley. Professional Paper 160. U.S. Geological Survey, Washington, D.C., USA.

Geologic GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available online (http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm). This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for Yosemite National Park using data model version 1.3.1

GRI digital geologic data are included on the attached CD and are available through the NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/App/Reference/Search?SearchType=Q). Enter “GRI” as the search text and select Yosemite National Park from the unit list.

The following components and geology data layers are part of the data set:

- Data in ESRI geodatabase, shapefile, and coverage GIS formats.
- Layer files with feature symbology (see table below).
- Federal Geographic Data Committee (FGDC)–compliant metadata
- An ancillary map information document (.hlp) that contains all of the ancillary map information and graphics, including geologic unit correlation tables, and map unit descriptions, legends, and other information captured from source maps.
- An ESRI map document file (.mxd) that displays the digital geologic data compiled for the entire park (yose_geology.mxd) and the glacial and postglacial deposits of Yosemite Valley (yova_geology.mxd). Map document files are also available for the individual quadrangle maps.

Table 7. Data layers in the Compiled Yosemite National Park Bedrock and Surficial GIS data (yose_geology.mxd).

Data Layer	Data Layer Code*	On Overview Graphic Sheets 1 or 2?
Cross Section Lines	xxxxsec	No
Observation, Observed Extent and Trend Lines	xxxxlin	No
Geologic Attitude and Observation Points	xxxxatd	No
Geologic Observation Localities	xxxxgol	No
Geologic Sample Localities	xxxxgsl	No
Mine Point Features	xxxxmin	No
Fault, Fold and Other Map Symbology	xxxxsym	No
Volcanic Point Features	xxxxvpf	No
Volcanic Line Features	xxxxvlf	No
Mine Area Feature Boundaries	xxxxmafa	No
Mine Area Features	xxxxmaf	No
Glacial Feature Lines	xxxxgfl	No
Glacial Area Feature Boundaries	xxxxgafa	No
Glacial Area Features	xxxxgaf	No
Geologic Line Features	xxxxglf	No
Folds	xxxxfld	No
Faults	xxxxflt	No
Linear Dikes	xxxxdke	Sheet 1
Linear Geologic Units	xxxxgln	No
Dike Swarm Contacts	xxxxdksa	Sheet 1
Dike Swarms	xxxxdks	Sheet 1
Deformation Area Contacts	xxxxdefa	No
Deformation Areas	xxxxdef	No
Surficial Contacts	xxxxsura	Sheets 1 and 2
Surficial Units	xxxxsur	Sheets 1 (simplified units) and 2
Geologic Contacts	xxxxglga	Sheets 1 and 2
Geologic Units	xxxxglg	Sheets 1 (simplified units) and 2

Note: * = xxxx refers to the four-letter code associated with the compiled GIS data (YOSE) or individual quadrangle maps as described in the GIS Readme file (see included DVD or digital GIS data).

Table 8. Data layers in the Glacial and Postglacial Deposits of Yosemite Valley Surficial GIS data.

Data Layer	Data Layer Code	On Overview Graphic Sheets 3 or 4?
Glacial Feature Points	yovagfp	Sheet 4
Glacial Feature Lines	yovamor	Sheet 4
Glacial Area Feature Boundaries	yovagfa	Sheet 4
Glacial Area Features	yovaagf	Sheet 4
Surficial Contacts	yovasura	Sheet 3
Surficial Units	yovasur	Sheet 3

Geologic Map Overview Graphics

The Geologic Map Overview Graphics (in pocket) display the GRI digital geologic data draped over a shaded relief image of the park and surrounding area. For graphic clarity and legibility, not all GIS feature classes may be visible on the overviews, as indicated in the above table. Cartographic elements and basic geographic information have been added to overviews. Digital elevation data and geographic information, which are part of the overview graphics, are not included with the GRI digital geologic GIS data for the park, but are available online from a variety of sources.

The Geologic Map Overview Graphics are separated into four sheets for Yosemite National Park:

- Sheet 1: Simplified Geologic Map
- Sheet 2: Detailed Map of Yosemite Valley
- Sheet 3: Glacial and Postglacial Deposits of Yosemite Valley
- Sheet 4: Glacial Extents of Yosemite Valley

Map Unit Properties Tables

The geologic units listed in the Map Unit Properties Tables (in pocket) correspond to the accompanying digital geologic data. Following the structure of the report, the table summarizes the geologic issues, features, and processes, and geologic history associated with each map unit. The table also lists the geologic time period, map unit symbol, and a geologic description of the unit.

There are two Map Unit Properties Tables for Yosemite National Park.

- Map Unit Properties Table A: Yosemite National Park Compiled Bedrock and Surficial Map. This table encompasses the compiled, park-wide bedrock and surficial geologic maps. Refer to overview graphic sheets 1 and 2. For graphic clarity, geologic map units were grouped together and simplified as described in the table for display on overview graphic sheet 1.
- Map Unit Properties Table B: Yosemite Valley Glacial and Postglacial Deposits, Yosemite National Park. This table encompasses the glacial and postglacial deposits of Yosemite Valley as mapped by Matthes (1930). Refer to overview graphic sheets 3 and 4.

Use Constraints

Graphic and written information provided in this section is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the overview graphic. Based on the source map scale and U.S. National Map Accuracy Standards, geologic features represented in the geologic map data are horizontally within the specified distance of their true location (table 9).

Please contact GRI with any questions.

Table 9. Maximum inaccuracy of geologic feature location for map scales present in Yosemite National Park digital geologic data.

Map Scale	Maximum Inaccuracy	
	meters	feet
1:62,500 (sheets 1 and 2)	32	104
1:48,000 (sheets 1 and 2)	24	80
1:24,000 (sheets 3 and 4)	12	40

Distance is determined from U.S. National Map Accuracy Standards and source map scale. Sheet numbers refer to Geologic Map Overview Graphics (in pockets).

Glossary

This glossary contains brief definitions of geologic terms used in this report. Not all geologic terms used are listed. Definitions are based on those in the American Geological Institute Glossary of Geology *(fifth edition; 2005). Additional definitions and terms are available at: http://geomaps.wr.usgs.gov/parks/misc/glossarya.html.*

ablation. All processes by which snow and ice are lost from a glacier, including melting, evaporation (sublimation), wind erosion, and calving.

ablation till. Loosely consolidated rock debris, formerly in or on a glacier, which accumulated in place as the surface ice was removed by ablation.

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

accretion. The gradual addition of new land to old by the deposition of sediment or emplacement of landmasses onto the edge of a continent at a convergent margin.

accretionary prism. A wedge-shaped body of deformed rock consisting of material scraped off of subducting oceanic crust at a subduction zone. Accretionary prisms form in the same manner as a pile of snow in front of a snowplow.

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."

alkali. Silicate minerals that contain alkali metals (sodium, potassium) but little calcium, e.g. the alkali feldspars.

allochthon. A mass of rock or fault block that has been moved from its place of origin by tectonic processes; commonly underlain by décollements.

alluvium. Stream-deposited sediment.

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

amphibole. A common group of rock-forming silicate minerals. Hornblende is the most abundant type.

amygdule. A gas cavity or vesicle in an igneous rock, which is filled with secondary minerals ("amygdaloidal" describes rocks with amygdules).

andesite. Fine-grained volcanic rock commonly associated with subduction zone volcanoes. Named for the subduction zone volcanoes of the Andes Mountains.

anhedral. A grain lacking well-developed crystal faces.

aplite. A light-colored intrusive igneous rock characterized by a fine-grained texture. Emplaced at a relatively shallow depth beneath Earth's surface.

arc. See "volcanic arc" and "magmatic arc."

arête. A rocky sharp-edged ridge or spur, commonly present above the snowline in rugged mountains sculptured by glaciers. The feature results from the continued backward growth of the walls of adjoining cirques.

argillite. A compact rock, derived from mudstone or shale, more highly cemented than either of those rocks. It does not easily split like of shale or have the cleavage of slate. It is regarded as a product of low-temperature metamorphism.

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

asthenosphere. Earth's relatively weak layer or shell below the rigid lithosphere.

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 (structural). A doubly plunging syncline in which rocks dip inward from all sides.

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

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.

bedrock. A general term for the rock that underlies soil or other unconsolidated, surficial material.

bergschrund. The crevasse occurring at the head of an alpine glacier that separates the moving snow and ice of the glacier from the relatively immobile snow and ice adhering to the headwall of a cirque.

biotite. A widely distributed and important rock-forming mineral of the mica group. Forms thin, flat sheets.

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

breccia (volcanic). A coarse-grained, generally unsorted volcanic rock consisting of partially welded angular fragments of ejected material such as tuff or ash.

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

calc-silicate rock. A metamorphic rock consisting mainly of calcium-bearing silicates and formed by metamorphism of impure limestone or dolomite.

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

calcite. A common rock-forming mineral: $CaCO_3$ (calcium carbonate).

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.
carbonate. A mineral that has CO_3^{-2} as its essential component (e.g., calcite and aragonite).
carbonate rock. A rock consisting chiefly of carbonate minerals (e.g., limestone, dolomite, or carbonatite).
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).
chemical weathering. Chemical breakdown of minerals at Earth's surface via reaction with water, air, or dissolved substances; commonly results in a change in chemical composition more stable in the current environment.
chert. A extremely hard sedimentary rock with conchoidal (smooth curved surface) fracturing. It consists chiefly of interlocking crystals of quartz Also called "flint."
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.
clast. An individual grain or rock fragment in a sedimentary rock, produced by the physical disintegration of a larger rock mass.
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]).
claystone. Lithified clay having the texture and composition of shale but lacking shale's fine layering and fissility (characteristic splitting into thin layers).
cleavage (mineral). The tendency of a mineral to break preferentially in certain directions along planes of weaknesses in the crystal structure.
columnar joints. Parallel, prismatic columns, polygonal in cross section, in basaltic flows and sometimes in other extrusive and intrusive rocks; they form as a result of contraction during cooling.
conglomerate. A coarse-grained, generally unsorted, sedimentary rock consisting of cemented, rounded clasts larger than 2 mm (0.08 in).
conodont. One of a large number of small, disjunct fossil elements assigned to the order Conodontophorida, phosphatic in composition and commonly tooth-like in form but not necessarily in function.
contact metamorphism. Changes in rock as a result of contact with an igneous body.
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 rifting. Process by which a region of crust undergoes extension (pulling apart), resulting in the formation of many related normal faults, and often associated with volcanic activity.
continental shelf. The shallowly submerged part of a continental margin extending from the shoreline to the continental slope with water depths less than 200 m (660 ft).
continental slope. The relatively steep slope from the outer edge of the continental shelf down to the more gently sloping ocean depths of the continental rise or abyssal plain.
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.
core. The central part of Earth, beginning at a depth of about 2,900 km (1,800 mi), probably consisting of iron-nickel alloy.
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").
crevasse. A deep fissure or crack in a glacier, caused by stresses resulting from differential movement over an uneven surface. Crevasses may be as much as 100 m (330 ft) deep.
cross section. A graphical interpretation of geology, structure, and/or stratigraphy in the third (vertical) dimension based on mapped and measured geological extents and attitudes depicted in a vertically oriented plane.
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.
cutbank. A steep, bare slope formed by lateral erosion of a stream.
dacite. A fine-grained extrusive igneous rock similar to andesite but with less calcium-plagioclase minerals and more quartz.
debris flow. A moving mass of rock fragments, soil, and mud, in which more than half the particles of which are larger than sand size.
deformation. A general term for the processes of faulting, folding, and shearing of rocks as a result of various Earth forces such as compression (pushing together) and extension (pulling apart).
detritus. A collective term for lose rock and mineral material that is worn off or removed by mechanical means.
dike. A narrow igneous intrusion that cuts across bedding planes or other geologic structures.
diorite. A type of plutonic igneous rock. It is the approximate intrusive equivalent of andesite.
divergent boundary. An active boundary where tectonic plates are moving apart (e.g., a spreading ridge or continental rift zone).
dome. General term for any smoothly rounded landform or rock mass. More specifically refers to an elliptical uplift in which rocks dip gently away in all directions.

downcutting. Stream erosion process in which the cutting is directed in primarily downward, as opposed to lateral erosion.
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. Includes unstratified material (till) and stratified deposits (outwash plains and fluvial deposits).
ephemeral stream. A stream that flows briefly only in direct response to precipitation in the immediate locality and whose channel is at all times above the water table.
epicontinental. Describes a geologic feature situated on the continental shelf or on the continental interior. An "epicontinental sea" is one example.
escarpment. A steep cliff or topographic step resulting from vertical displacement on a fault or by mass movement. Also called a "scarp."
euhedral. A grain bounded by perfect crystal faces; well-formed.
exfoliation. The breakup, spalling, peeling, or flaking of layers or concentric sheets from an exposed rock mass caused by differential stresses due to thermal changes or a reduction in pressure when overlying rocks erode away.
extension. A type of strain resulting from forces "pulling apart." Opposite of compression.
extrusive. Describes molten (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. An igneous rock containing abundant light-colored minerals.
flat slab subduction. Refers to a tectonic plate being subducted beneath another tectonic plate at a relatively shallow angle.
floodplain. The surface or strip of relatively smooth land adjacent to a river channel and formed by the river. Covered with water when the river overflows its banks.
fold. A curve or bend of an originally flat or planar structure such as rock strata, bedding planes, or foliation that is usually a product of deformation.
foliation. A preferred arrangement of crystal planes in minerals. In metamorphic rocks, the term commonly refers to a parallel orientation of planar minerals such as micas.
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).
frost wedging. The breakup of rock due to the expansion of water freezing in fractures.
gabbro. A group of dark-colored, intrusive igneous rocks. The intrusive equivalent of basalt.
geology. The study of Earth including its origin, history, physical processes, components, and morphology.
glacial erratic. Boulders transported by glaciers some distance from their point of origin.
glaciomarine. Describes the accumulation of glacially eroded, terrestrially derived sediment in the marine environment.
granite. An intrusive igneous (plutonic) rock composed primarily of quartz and feldspar. Mica and amphibole minerals are also common. Intrusive equivalent of rhyolite.
graben. A down-dropped structural block bounded by steeply dipping, normal faults (also see "horst").
granodiorite. A group of intrusive igneous (plutonic) rocks containing quartz, plagioclase, and potassium feldspar minerals with biotite, hornblende, or, more rarely, pyroxene, as the mafic components.
greywacke. A term commonly used in the field for a dark gray to dark green, very hard, dense sandstone of any composition but with a chlorite-rich matrix; these rocks have undergone deep burial.
greenstone. A general term for any compact dark green altered or metamorphosed basic igneous rock owing its color to chlorite, actinolite, or epidote minerals.
groundmass. The material between the large crystals in a porphyritic igneous rock. Can also refer to the matrix of a sedimentary rock.
grus. A silica-rich sand derived from the weathering of a parent rock, usually granite.
hanging valley. A tributary glacial valley whose mouth is high above the floor of the main valley, which was eroded by the main body of the glacier.
hanging wall. The mass of rock above a fault surface (also see "footwall").
hornblende. The most common mineral of the amphibole group. Hornblende is commonly black and occurs in distinct crystals or in columnar, fibrous, or granular forms.
horn. A high pyramidal peak with steep sides formed by the intersection walls of three or more cirques.
hornfels. A fine-grained rock composed of a mosaic of grains that are the same size in each dimension without preferred orientation. Typically formed by contact metamorphism, which occurs near the contact with an intrusion of molten material.
horst. Areas of relative "up" between grabens, representing the geologic surface left behind as grabens drop. The best example is the Basin-and-Range province of Nevada. The basins are grabens and the ranges are weathered horsts. Grabens become a locus for sedimentary deposition (also see "graben").
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.

imbrication. Commonly displayed by pebbles on a stream bed, where flowing water tilts the pebbles so that their flat surfaces dip upstream.

incision. The process whereby a downward-eroding stream deepens its channel or produces a narrow, steep-walled valley.

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

island arc. A line or arc of volcanic islands formed over and parallel to a subduction zone.

isotopic age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products; "absolute age" and "radiometric age" are often used in place of isotopic age but are less precise terms.

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

kaolinite. A common clay mineral with a high aluminum oxide content and white color.

labradorite. A colorless or dark mineral of the plagioclase feldspar group.

lahar. A mudflow composed chiefly of volcaniclastic materials on the flank of a volcano.

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

lapilli. Pyroclastics in the general size range of 2 to 64 mm (0.08 to 2.5 in.).

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. A strike slip fault on which the side opposite the observer has been displaced to the left. Synonymous with "sinistral fault."

lens. A sedimentary deposit characterized by converging surfaces, thick in the middle and thinning out toward the edges, resembling a convex lens.

leuco-. A prefix meaning "light-colored." Applied to light-colored igneous rocks that are relatively poor in mafic minerals.

levee. Raised ridge lining the banks of a stream. May be natural or artificial.

limb. Either side of a structural fold.

limestone. A sedimentary rock consisting chiefly of calcium carbonate, primarily in the form of the mineral calcite.

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.

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

magma reservoir. A chamber in the shallow part of the lithosphere from which volcanic materials are derived; the magma has ascended from a deeper source.

magmatic arc. Zone of plutons or volcanic rocks formed at a convergent boundary.

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

mass wasting. A general term for the downslope movement of soil and rock material under the direct influence of gravity.

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.

meander. Sinuous lateral curve or bend in a stream channel. An entrenched meander is incised, or carved downward into the surface of the valley in which a meander originally formed. The meander preserves its original pattern with little modification.

mechanical weathering. The physical breakup of rocks without change in composition. Synonymous with "physical weathering."

member. A lithostratigraphic unit with definable contacts; a member subdivides a formation.

meta–. A prefix used with the name of a sedimentary or igneous rock, indicating that the rock has been metamorphosed.

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.

miarolitic. Small irregular cavities in igneous rocks into which small crystals of the rock-forming minerals protrude.

mica. A prominent rock-forming mineral of igneous and metamorphic rocks. It has perfect basal cleavage meaning that it forms flat sheets. Biotite is in the mica group.

microcrystalline. A rock with a texture consisting of crystals only visible with a microscope.

micrographic. Said of the graphic texture of an igneous rock, distinguishable only with a microscope.

migmatite. A composite rock composed of igneous or igneous-appearing or metamorphic materials.

mineral. A naturally occurring, inorganic crystalline solid with a definite chemical composition or compositional range.

moraine. A mound, ridge, or other distinct accumulation of unsorted, unstratified glacial drift, predominantly till, deposited by glacial ice movement.

moulin. A roughly cylindrical, nearly vertical hole or shaft in the ice of a glacier, scoured out by swirling meltwater as it pours down from the surface.

neck (volcanic). An eroded, vertical, pipe-like intrusion that represents the vent of a volcano.

Neoglacial. Describes the period of glacial readvance during the late Holocene, the most recent being the Little Ice Age (from the 1500s until the mid 1800s).

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.

olistolith. A large block or other rock mass (usually greater than 10 m or 33 ft) transported by submarine gravity sliding or slumping and included within a debris-flow deposit called an olistostrome.

orogeny. A mountain-building event.

outcrop. Any part of a rock mass or formation that is exposed or "crops out" at Earth's surface.

outwash. Glacial sediment transported and deposited by meltwater streams.

overbank deposit. Alluvium deposited outside a stream channel during flooding.

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. Rock from which soil, sediments, or other rocks are derived.

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 (compare to "active margin").

pegmatite. An exceptionally coarse-grained intrusive igneous rock, with interlocking crystals, usually found in irregular dikes, lenses, and veins, especially at the margins of batholiths.

pendant. A solutional remnant hanging from the ceiling or wall of a cave.

phenocryst. A coarse (large) crystal in a porphyritic igneous rock.

phonolite. A group of fine-grained extrusive rocks primarily composed of alkali feldspar.

phyllite. A metamorphosed rock, intermediate in grade between slate and mica schist, with minute crystals of graphite, sericite, or chlorite that impart a silky sheen to the surfaces ("schistosity").

plagioclase. An important rock-forming group of feldspar minerals.

plastic. Capable of being deformed permanently without rupture.

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.

pluton (plutonic). A body of intrusive igneous rock that crystallized at some depth beneath Earth's surface.

poikilitic. Said of the texture of an igneous rock in which small grains of one mineral (e.g. plagioclase) are irregularly scattered within a typically anhedral larger crystal of another mineral (e.g. pyroxene).

point bar. A low ridge of sand and gravel deposited in a stream channel on the inside of a meander where flow velocity slows.

porphyry. An igneous rock consisting of abundant coarse crystals in a fine-grained matrix.

porphyritic. Describes an igneous rock wherein the rock contains conspicuously large crystals in a fine-grained groundmass.

potassium feldspar. A feldspar mineral rich in potassium (e.g., orthoclase, microcline, sanidine, adularia).

Principle of uniformity. The assumption of uniformity of causes or processes throughout time and space; the uniformity of natural laws. Not synonymous with the uniformitarianism of Charles Lyell, who constrained throughout geologic time both the intensity and frequency and the kinds of processes seen today.

pull-apart basin. A topographic depression created by an extensional bend or extensional overstep along a strike-slip fault.

pyroxene. A common rock-forming mineral. It is characterized by short, stout crystals.

quartzite. Metamorphosed quartz sandstone.

radiometric age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products.

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").

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.

rift. A region of crust where extension results in formation of many related normal faults, often associated with volcanic activity.

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.

rock. A solid, cohesive aggregate of one or more minerals.

rockfall. Mass wasting process where rocks are dislodged and move downslope rapidly; it is the fastest mass wasting process.

sand. A clastic particle smaller than a granule and larger than a silt grain, having a diameter in the range of 1/16 mm (0.0025 in) to 2 mm (0.08 in).

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.

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.

sericite. A white, fine-grained potassium mica occurring in small scales and flakes as an alteration product of various aluminosilicate minerals, having a silky luster, and found in various metamorphic rocks.

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.

silicate. A compound whose crystal structure contains the SiO_4 tetrahedra.

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.

sinkhole. A circular depression with subterranean drainage and is commonly funnel-shaped.

slate. A compact, fine-grained metamorphic rock that can be split into slabs and thin plates. Most slate was formed from shale.

slope. The inclined surface of any geomorphic feature or measurement thereof. Synonymous with "gradient."

sodic. Containing sodium.

spreading center. A divergent boundary where two lithospheric plates are spreading apart. It is a source of new crustal material.

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

stratification. The accumulation, or layering of sedimentary rocks in strata. Tabular, or planar, stratification refers to essentially parallel surfaces. Cross-stratification refers to strata inclined at an angle to the main stratification.

stratigraphy. The geologic study of the origin, occurrence, distribution, classification, correlation, and age of rock layers, especially sedimentary rocks.

stream. Any body of water moving under gravity flow in a clearly confined channel.

stream channel. A long, narrow depression shaped by the concentrated flow of a stream and covered continuously or periodically by water.

stream terrace. Step-like benches surrounding the present floodplain of a stream due to dissection of previous flood plain(s), stream bed(s), and/or valley floor(s).

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.

structural geology. The branch of geology that deals with the description, representation, and analysis of structures, chiefly on a moderate to small scale. The subject is similar to tectonics, but the latter is generally used for the broader regional or historical phases.

structure. The attitude and relative positions of the rock masses of an area resulting from such processes as faulting, folding, and igneous intrusions.

subaerial. Describes conditions and processes that exist or operate in the open air on or immediately adjacent to the land surface.

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

subhedral. A grain partly bounded by crystal faces; intermediate between euhedral and anhedral.

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

suture. The linear zone where two continental landmasses become joined via obduction.

system (stratigraphy). The group of rocks formed during a period of geologic time.

talus. Rock fragments, usually coarse and angular, lying at the base of a cliff or steep slope from which they have been derived.

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

tectonics. The geologic study of the broad structural architecture and deformational processes of the lithosphere and asthenosphere.

terrace. A relatively level bench or step-like surface breaking the continuity of a slope (also see "stream terrace").

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

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

terrigenous. Derived from the land or a continent.

theory. A hypothesis that has been rigorously tested against further observations or experiments to become a generally accepted tenet of science.

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.

tonalite. A type of igneous, intrusive (plutonic) rock composed primarily of quartz and plagioclase with 10% or less alkali feldspar. Pyroxenes and amphiboles are common accessory minerals.

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.

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

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

tremolite. A white to dark-gray monoclinic mineral of the amphibole group. It has varying amounts of iron, and may contain manganese and chromium. It occurs in long blade-shaped or short stout prismatic crystals and also in columnar, fibrous, or granular masses or compact aggregates, generally in metamorphic rocks such as crystalline dolomitic limestone and talc schists.

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

trondhjemite. A light-colored plutonic rock primarily composed of sodic plagioclase (esp. oligoclase), quartz, sparse biotite, and little or no alkali feldspar.

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

tuffaceous. A non-volcanic, clastic sedimentary rock that contains mixtures of ash-size pyroclasts.

type locality. The geographic location where a stratigraphic unit (or fossil) is well displayed, formally defined, and derives its name. The place of original description.

unconformity. A substantial break or gap in the geologic record where a rock unit is overlain by another that is not next in stratigraphic succession.

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.

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

volcanic arc. A commonly curved, linear, zone of volcanoes above a subduction zone.

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

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Additional References

This section lists additional references, resources, and websites that may be of use to resource managers. Web addresses are current as of July 2012.

Geology of National Park Service Areas

National Park Service Geologic Resources Division (Lakewood, Colorado): http://nature.nps.gov/geology/

NPS Geologic Resources Inventory: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm

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NPS Geoscientist-in-the-Parks (GIP) internship and guest scientist program: http://www.nature.nps.gov/geology/gip/index.cfm

NPS Views Program (Geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a wide variety of geologic parks): http://www.nature.nps.gov/views/layouts/Main.html#/Views/.

NPS Resource Management Guidance and Documents

1998 National Parks Omnibus Management Act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf

NPS 2006 Management Policies (Chapter 4; Natural Resource Management): http://www.nps.gov/policy/mp/policies.html#_Toc157232681

NPS-75: Natural Resource Inventory and Monitoring Guideline: http://www.nature.nps.gov/nps75/nps75.pdf

NPS Natural Resource Management Reference Manual #77: http://www.nature.nps.gov/Rm77/

Geologic Monitoring Manual:
Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado, USA. http://nature.nps.gov/geology/monitoring/index.cfm

NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://etic.nps.gov/

Geological Surveys and Societies

California Geological Survey: http://www.consrv.ca.gov/cgs/Pages/Index.aspx.

U.S. Geological Survey: http://www.usgs.gov/

Geological Society of America: http://www.geosociety.org/

American Geological Institute: http://www.agiweb.org/

Association of American State Geologists: http://www.stategeologists.org/

U.S. Geological Survey Reference Tools

U.S. Geological Survey National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/

U.S. Geological Survey Geologic Names Lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html

U.S. Geological Survey Geographic Names Information System (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/

U.S. Geological Survey GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on “Map Locator”)

U.S. Geological Survey Publications Warehouse (USGS publications, many available online): http://pubs.er.usgs.gov

U.S. Geological Survey Tapestry of Time and Terrain (descriptions of physiographic provinces): http://tapestry.usgs.gov/Default.html

Appendix: Scoping Meeting Participants

The following people attended the GRI scoping meeting for Yosemite National Park, held on September 25–26, 2002. Discussions during that meeting supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).

Name	Affiliation	Position
Allen, Lindy	NPS, Geologic Resources Division	Administrative Assistant
Bumgardner, Steve		Videographer
Butler, Mark	NPS, Yosemite National Park	Physical Scientist
Tim Connors	NPS, Geologic Resources Division	Geologist
Despain, Joel	NPS, Sequoia-Kings Canyon National Parks	Cave Specialist
Dulen, Deanna	NPS, Devils Postpile National Monument	Superintendent
Galipeau, Russell	NPS, Yosemite National Park	Chief of Cultural Resources
Glazner, Allan	University of North Carolina – Chapel Hill	Professor
Gregson, Joe	NPS, Geologic Resources Division	Geologist
Heise, Bruce	NPS, Geologic Resources Division	Geologist
Huber, King	U.S. Geological Survey	Geologist
Meyer, Joe	NPS, Yosemite National Park	GIS Specialist
Murchey, Bonnie	U.S. Geological Survey	Geologist
VanWagtendonk, Jan	U.S. Geological Survey	Research Forester

NPS 104/116306, August 2012

National Park Service
U.S. Department of the Interior

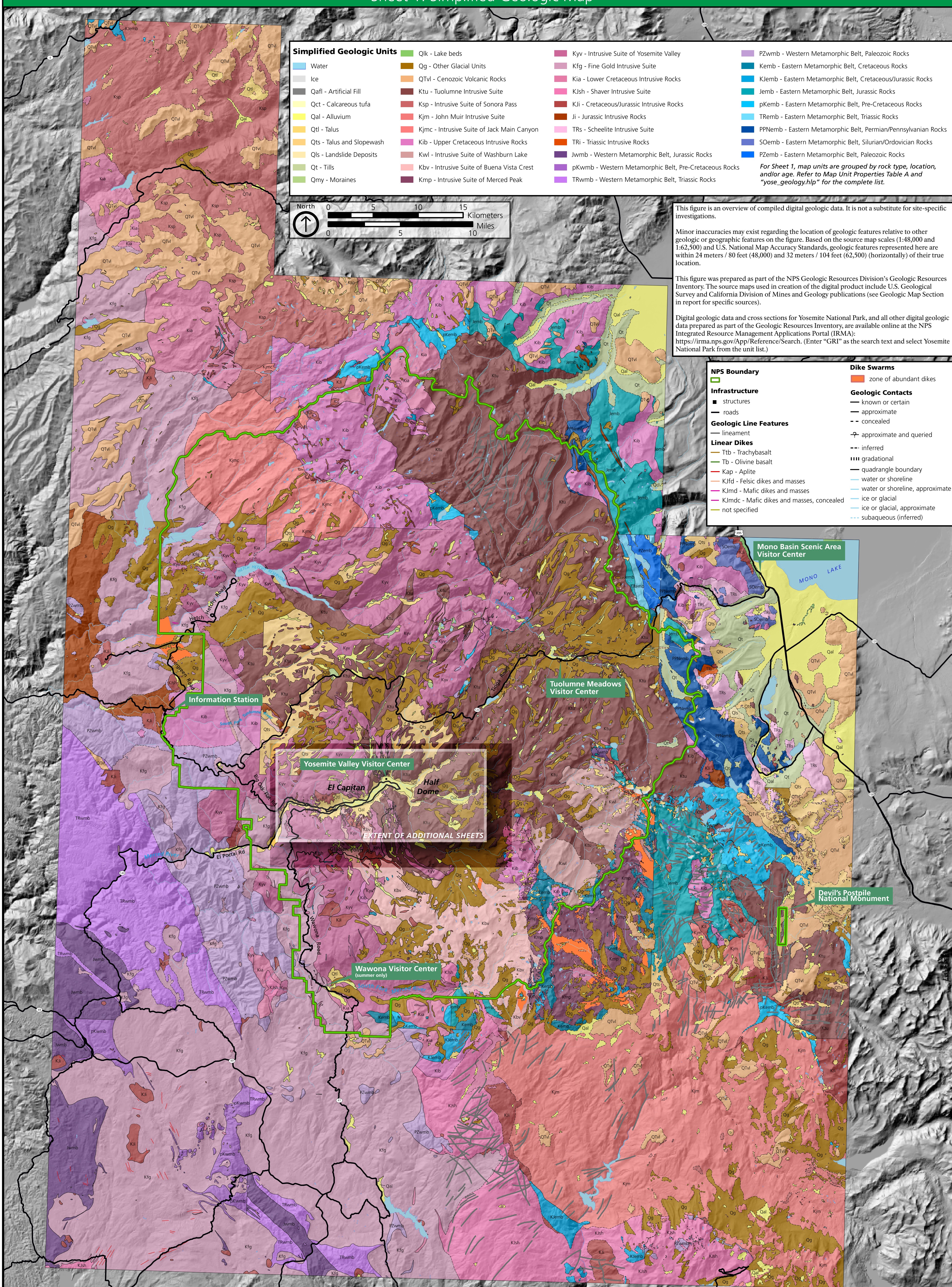
Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

www.nature.nps.gov

National Park Service
U.S. Department of the Interior

Overview of Digital Geologic Data for
Yosemite National Park

Sheet 1: Simplified Geologic Map



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August 2012

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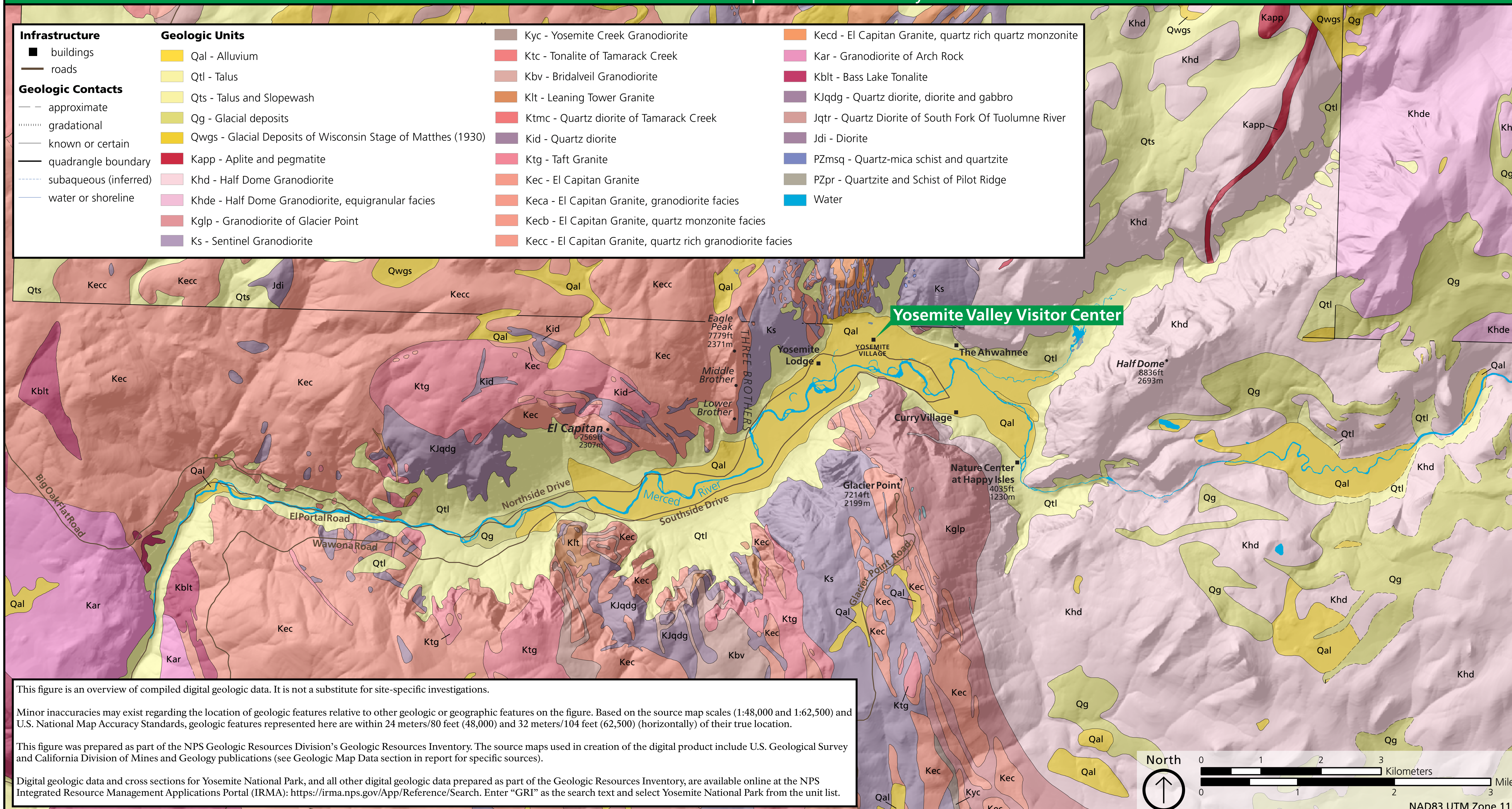
U.S. Department of the Interior

Overview of Digital Geologic Data for Yosemite National Park

Sheet 2: Detailed Map of Yosemite Valley



Infrastructure
- buildings
- roads

Geologic Contacts
- approximate
- gradational
- known or certain
- quadrangle boundary
- subaqueous (inferred)
- water or shoreline

Geologic Units
- Qal - Alluvium
- Qtl - Talus
- Qts - Talus and Slopewash
- Qg - Glacial deposits
- Qwgs - Glacial Deposits of Wisconsin Stage of Matthes (1930)
- Kapp - Aplite and pegmatite
- Khd - Half Dome Granodiorite
- Khde - Half Dome Granodiorite, equigranular facies
- Kglp - Granodiorite of Glacier Point
- Ks - Sentinel Granodiorite
- Kyc - Yosemite Creek Granodiorite
- Ktc - Tonalite of Tamarack Creek
- Kbv - Bridalveil Granodiorite
- Klt - Leaning Tower Granite
- Ktmc - Quartz diorite of Tamarack Creek
- Kid - Quartz diorite
- Ktg - Taft Granite
- Kec - El Capitan Granite
- Keca - El Capitan Granite, granodiorite facies
- Kecb - El Capitan Granite, quartz monzonite facies
- Kecc - El Capitan Granite, quartz rich granodiorite facies
- Kecd - El Capitan Granite, quartz rich quartz monzonite
- Kar - Granodiorite of Arch Rock
- Kblt - Bass Lake Tonalite
- KJqdg - Quartz diorite, diorite and gabbro
- Jqtr - Quartz Diorite of South Fork Of Tuolumne River
- Jdi - Diorite
- PZmsq - Quartz-mica schist and quartzite
- PZpr - Quartzite and Schist of Pilot Ridge
- Water

This figure is an overview of compiled digital geologic data. It is not a substitute for site-specific investigations.

Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the figure. Based on the source map scales (1:48,000 and 1:62,500) and U.S. National Map Accuracy Standards, geologic features represented here are within 24 meters/80 feet (48,000) and 32 meters/104 feet (62,500) (horizontally) of their true location.

This figure was prepared as part of the NPS Geologic Resources Division's Geologic Resources Inventory. The source maps used in creation of the digital product include U.S. Geological Survey and California Division of Mines and Geology publications (see Geologic Map Data section in report for specific sources).

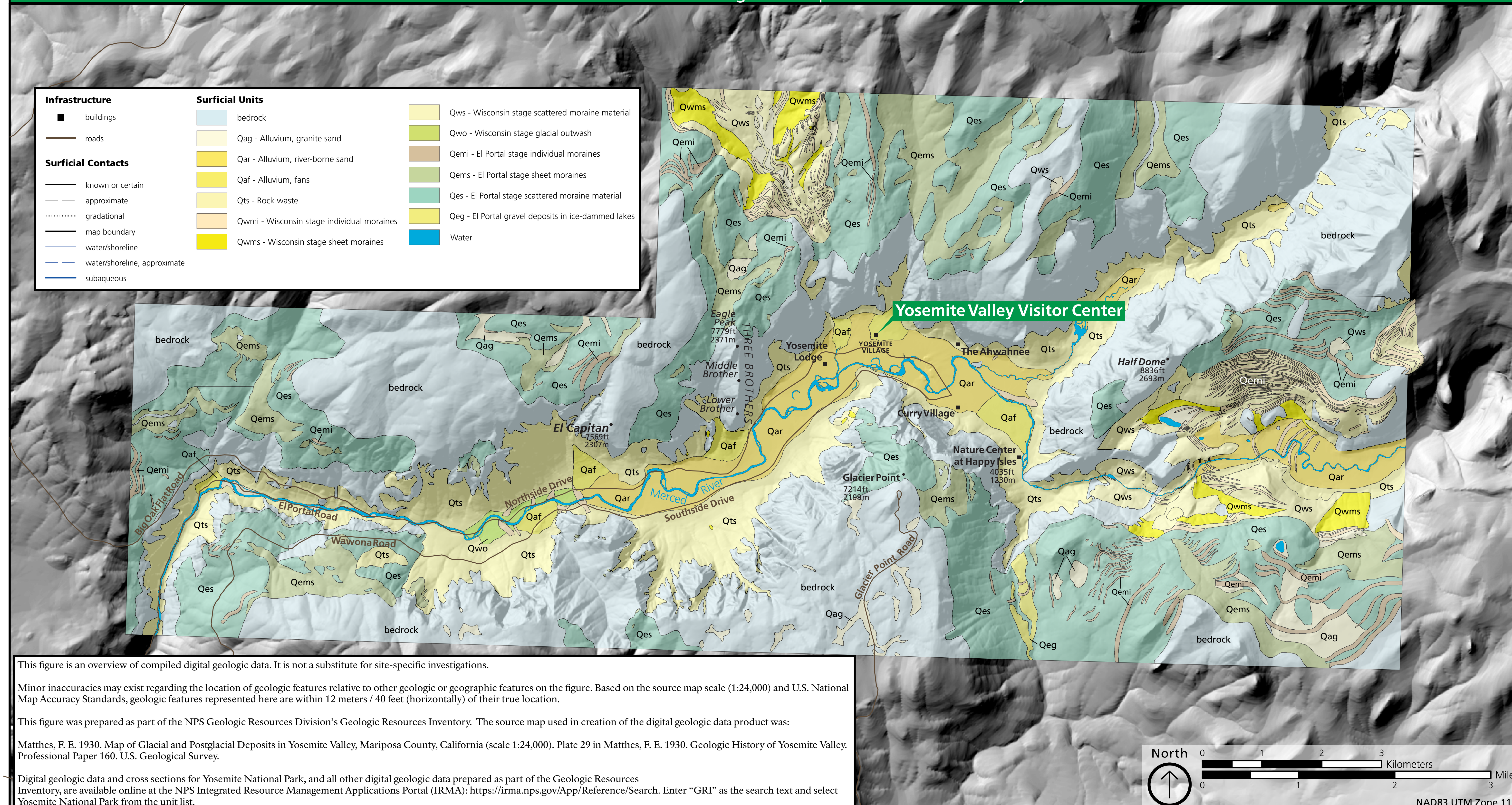
Digital geologic data and cross sections for Yosemite National Park, and all other digital geologic data prepared as part of the Geologic Resources Inventory, are available online at the NPS Integrated Resource Management Applications Portal (IRMA): https://irma.nps.gov/App/Reference/Search. Enter "GRI" as the search text and select Yosemite National Park from the unit list.

Produced by the Geologic Resources Inventory

July 2012

Overview of Digital Geologic Data for Yosemite National Park

Sheet 3: Glacial and Postglacial Deposits of Yosemite Valley



This figure is an overview of compiled digital geologic data. It is not a substitute for site-specific investigations.

Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the figure. Based on the source map scale (1:24,000) and U.S. National Map Accuracy Standards, geologic features represented here are within 12 meters / 40 feet (horizontally) of their true location.

This figure was prepared as part of the NPS Geologic Resources Division's Geologic Resources Inventory. The source map used in creation of the digital geologic data product was:

Matthes, F. E. 1930. Map of Glacial and Postglacial Deposits in Yosemite Valley, Mariposa County, California (scale 1:24,000). Plate 29 in Matthes, F. E. 1930. Geologic History of Yosemite Valley. Professional Paper 160. U.S. Geological Survey.

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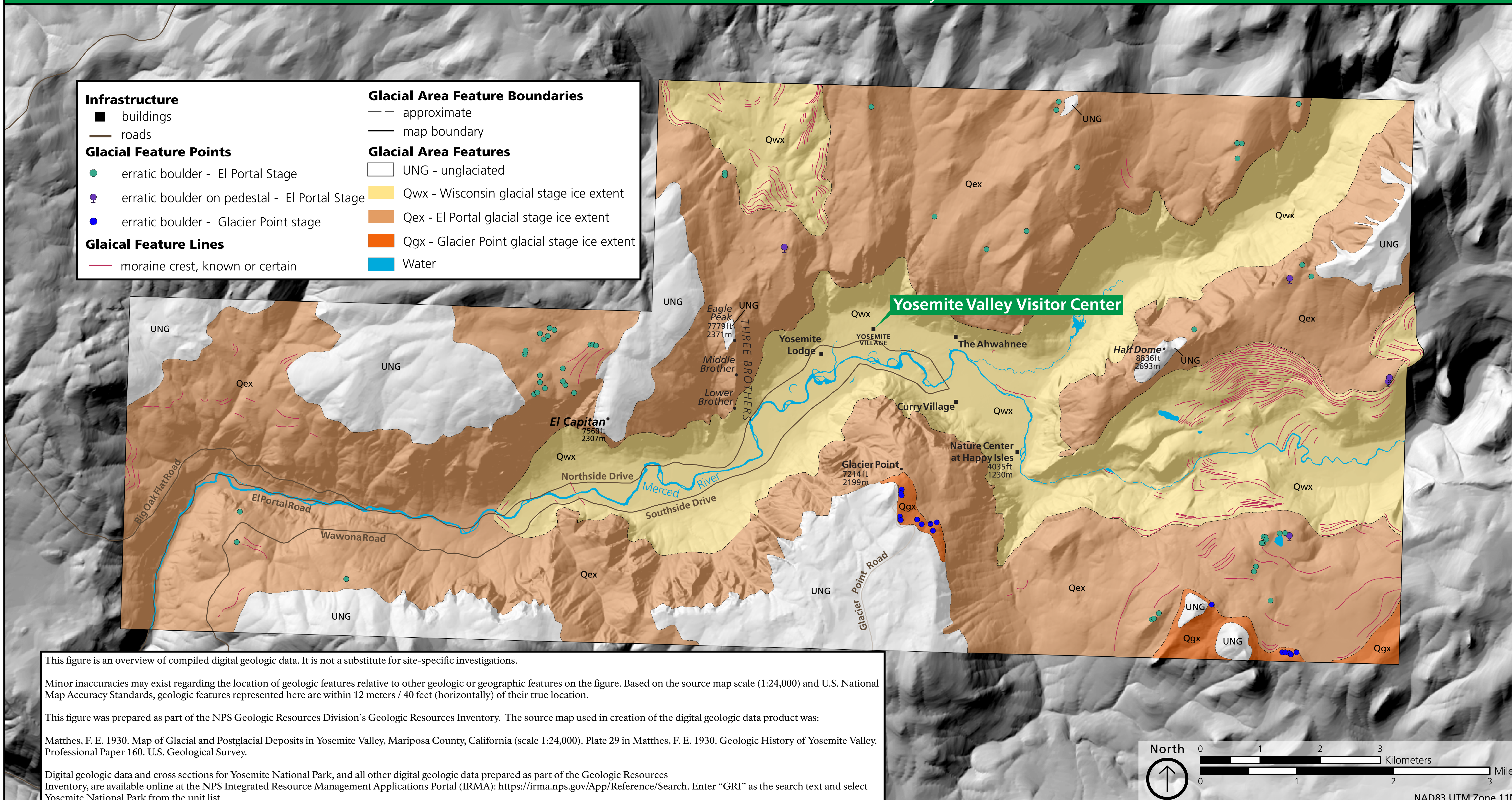
July 2012

Overview of Digital Geologic Data for Yosemite National Park

Sheet 4: Glacial Extents of Yosemite Valley



This figure is an overview of compiled digital geologic data. It is not a substitute for site-specific investigations.

Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the figure. Based on the source map scale (1:24,000) and U.S. National Map Accuracy Standards, geologic features represented here are within 12 meters / 40 feet (horizontally) of their true location.

This figure was prepared as part of the NPS Geologic Resources Division's Geologic Resources Inventory. The source map used in creation of the digital geologic data product was:

Matthes, F. E. 1930. Map of Glacial and Postglacial Deposits in Yosemite Valley, Mariposa County, California (scale 1:24,000). Plate 29 in Matthes, F. E. 1930. Geologic History of Yosemite Valley. Professional Paper 160. U.S. Geological Survey.

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Produced by the Geologic Resources Inventory

July 2012

Map Unit Properties Table A: Compiled Bedrock and Surficial Map, Yosemite National Park

Gray-shaded rows indicate units not mapped within the park. Bold text corresponds to sections of the report. Colors in Map Unit columns correspond to Geologic Map Overview sheets 1 (simplified map, entire park) and 2 (detailed map, Yosemite Valley).

Age	Simplified Map Unit (Symbol) *Overview Sheet 1*	Map Unit (Symbol) *Colored if present on Overview Sheet 2*	Geologic Description	Geologic Issues	Geologic Features, Processes and General Location	Geologic History
Quaternary Surface and Glacial Rock Units						
QUATERNARY (Holocene)	Alluvium (Qal)	Alluvium (Qal)	Primarily gravel, sand, and silt that underlies meadows. Deposited by streams.	**Debris Flow and Flooding**—Overbank and floodplain deposits represent flood and debris-flow events.	**Recent Geomorphic Features (Fluvial)**—Meandering channel patterns, point bars, cutbanks, terraces, floodplains, and debris deposited during flooding.	These unconsolidated units in Yosemite National Park represent flooding and mass-wasting processes that have occurred throughout geologic time (principle of uniformity). Geologists study these recent deposits to better understand ancient depositional environments and their associated geologic units.
	Talus (Qtl)	Talus (Qtl)	Rock debris derived from cliffs. Talus piles are present at most cliff bases, especially in Yosemite Valley.	**Rockfalls, Rockslides and Rock Avalanches**—These mass-wasting deposits represent unpredictable movement of rock material from unstable slopes. They are hazards that affect visitor safety and park infrastructure (i.e., roads, trails, buildings, sewer lines, campgrounds). Triggering mechanisms vary. **Erosion**—Slopewash involves the transportation of rock and soil down a slope by rain. In general, slopewash presents a smaller hazard than rockfall.	**Talus Piles—**Large talus piles have formed beneath cliffs that contain abundant joints, such as The Rockslides (west of El Capitan).	
	Talus and Slopewash (Qts)	Talus and Slopewash (Qts)	Unconsolidated mixture of debris (soil and rocks) that may be washed down slopes by running water not confined to channels.		**Talus Piles**—Primarily mapped in the Hetch Hetchy Reservoir quadrangle in the park. May contain abundant volcanic pumice.	
	Landslide (Qls)	Landslide (Qls)	Unsorted debris deposits resulting from mass movement.		**Landslides**—Includes inactive rock glaciers. The unit is mapped primarily in the northern part of the park.	
	Other Glacial Units (Qg)	Glacial Units: Neoglacial and periglacial deposits (Qng)	Angular rock debris and talus with particle sizes ranging from sand to cobbles and boulders of 3 m (10 ft) or more from existing Holocene glaciers (neoglacial). Includes deposits in glacial features that form along the margins of existing glaciers or former post-Pleistocene glaciers (periglacial).	**Erosion**—Glacial deposits may form unstable slopes.	**Modern Glacial Features**—Exposed in the northern and eastern parts of the park in the Tower Peak, Matterhorn Peak, and Mono Craters quadrangles.	**Tension, Uplift, and Ice**—Present-day glaciers began forming about 500 years ago. The deposits reflect changing climatic conditions that are melting the glaciers.
		Glacial Units: Rock glaciers (Qrg)	Poorly sorted angular boulders and fine material with interstitial ice about 1 m (3.3 ft) below the surface.	None—Rock glaciers move slowly and are not a geologic issue.	**Modern Glacial Features**—Isolated deposits of limited areal extent exposed east of the eastern park boundary in the Mono Craters quadrangle.	**Tension, Uplift, and Ice**—Isolated deposits. Larger, mappable exposures lie east of the park.
QUATERNARY (Pleistocene)	Lake beds (Qlk)	Glacial Units: Lake beds (Qlk)	The source map does not provide a detailed description.	None—This unit lies outside of the park boundaries.	**Geomorphic Feature**—Borders the western edge of Mono Lake in the Mono Craters quadrangle.	**Tension, Uplift, and Ice**—Remnants of a large lake in the Mono Basin fed by Pleistocene glaciers.
	Other Glacial Units (Qg)	Glacial Units: Glacial deposits (Qg)	Primarily unconsolidated moraine and outwash deposits. Includes Tioga and Tahoe till.	None Significant	**Pleistocene Glacial Features (Depositional)**—Moraines	**Tension, Uplift, and Ice**—Late Pleistocene glacial deposits.
	Tills (Qcl)	Glacial Units: Tioga Till (Qti)	Unsorted till deposits. All granitic, volcanic, and metamorphic rocks are relatively fresh.	**Flooding—Qti** forms the El Capitan moraine in Yosemite Valley and may act as a natural dam during spring flooding of the Merced River.	**Pleistocene Glacial Features (Depositional)**—Sharp-crested moraines, usually with abundant boulders on the surface.	**Tension, Uplift, and Ice**—Tioga-age (26,000–18,000 years ago) glacial deposits.

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Age	Simplified Map Unit (Symbol) *Overview Sheet 1*	Map Unit (Symbol) *Colored if present on Overview Sheet 2*		Geologic Description	Geologic Issues	Geologic Features, Processes and General Location	Geologic History
QUATERNARY (Pleistocene)	Tills (Qcl)	Glacial Units	Till of Tenaya Glaciation (Qte)	Till deposits containing fresh metamorphic and volcanic boulders and moderately weathered granitic boulders.	None Significant—**Qti** and **Qta** deposits exposed at higher elevations in the Matterhorn Peak and Mono Craters quadrangles	**Pleistocene Glacial Features (Depositional)**—Sharp-crested, slightly eroded moraines in exposures of limited areal extent north of Twin Lakes, Matterhorn Peak quadrangle.	**Tension, Uplift, and Ice**—Described by Matthes (1930). Evidence of the Tenaya Glaciation has been eroded from Yosemite National Park.
			Tahoe Till (Qta, Qtao)	**Qta**: unsorted glacial till deposits. **Qtao**: older till of the Tahoe Glaciation mapped east of the park, east of Mono Pass.		**Pleistocene Glacial Features (Depositional)**—**Qta**: conspicuous, broad-crested, well-preserved moraines with deeply weathered granitic boulders, some of which have disintegrated into grus.	**Tension, Uplift, and Ice**—Tahoe-age (140,000–80,000 years ago) glacial deposits. Because they are older, these moraines are more subdued than the Tioga moraines.
			Till of Mono Basin Glaciation (Qmb)	Till deposits commonly containing deeply weathered granitic boulders. Fine-grained metamorphic and volcanic boulders are fresh.	None—These units lie outside of the park boundaries.	**Pleistocene Glacial Features (Depositional)**—Indistinct moraines with continuous crests east of Twin Lakes in the Matterhorn Peak quadrangle, north of the park.	**Tension, Uplift, and Ice**—Debate continues with regard to whether the Mono Basin Glaciation pre-dated the Tahoe Glaciation.
			Till of Sherwin Glaciation (Qsh)	Granitic boulders are deeply weathered and exfoliated. Fine-grained volcanic and metamorphic boulders are less weathered.		**Pleistocene Glacial Features (Depositional)**—Smooth, soil-covered moraines and other glacial deposits lacking conspicuous depositional form. Exposed east of Mt. Dana and the park.	**Tension, Uplift, and Ice**—Sherwin Glaciation occurred approximately 800,000 years ago (Pleistocene).
			Old Till (Qto)	Till deposits probably related to the Sherwin Glaciation. The source map does not provide a detailed description.	None Documented	**Pleistocene Glacial Features (Depositional)**—Isolated exposures along the eastern boundary of the park near Mt. Lewis and Gem Pass, Mono Craters quadrangle.	**Tension, Uplift, and Ice**—Possible remnants of the Sherwin Glaciation.
	Moraines (Qmy)		Moraine (Qmy)	Described as younger than the Wisconsin Stage of Matthes (1930).	None—Mapped in river valleys and on the surface of relatively flat topography.	**Pleistocene Glacial Features (Depositional)**—Moraines mapped in the Hetch Hetchy Reservoir quadrangle.	**Tension, Uplift, and Ice**—Mapped by Kistler (1973) after work done by Matthes (1930).
	Other Glacial Units (Qg)		Wisconsin Stage of Matthes (1930) (Qwgs)	Glacial till. The source map does not provide a detailed description.		**Pleistocene Glacial Features (Depositional)**—Moraines mapped in the Hetch Hetchy Reservoir quadrangle by Kistler (1973). Mapped as **Qti** by Huber et al. (1989).	**Tension, Uplift, and Ice**—Matthes (1930) mapped lateral moraines left by the Tuolumne Glacier in Hetch Hetchy Canyon and believed the valley was traversed by a glacier "60 mi long and 4,000 ft thick," which was 1,000 ft thicker than the glacier in Yosemite Valley.
			Deposits of El Portal Glaciation (Qegs)	Glacial till. The source map does not provide a detailed description.		**Pleistocene Glacial Features (Depositional)**—Deposits mapped in the Hetch Hetchy Reservoir quadrangle by Kistler (1973). Mapped as **Qti** and **Qta** by Huber et al. (1989).	**Tension, Uplift, and Ice**—Matthes (1930) described cobbles and fragments of granitic rocks, which he considered to be morainal material, scattered on a slate and quartzite bedrock surface about 850 m (2,800 ft) above the canyon floor west of El Portal.
Quaternary and Tertiary Volcanic and Sedimentary Rock Units							
QUATERNARY	Cenozoic Volcanic Rocks (QTvl)	Basalt of Red Cones (Qbr)		Basalt cinders that are typically scoriaceous (having large gas holes) with prominent phenocrysts of plagioclase and olivine.	None—These units lie outside of the park boundaries.	Cinders exposed in the Red Cones, Devils Postpile quadrangle, southeast of the park.	Remnants of a 10,000-year-old volcanic eruption associated with the Long Valley Caldera.
		Andesite of Pumice Butte (Qap)		Cinder cones and associated flows. Typically, scoriaceous and nonporphyritic.		**Volcanic Bedrock**—Cinder cones and associated flows are located in the Devils Postpile quadrangle, southeast of the park.	**Tension, Uplift, and Ice**—Unit includes dacite that forms two knobs in northwest part of outcrop area, which may be older than the andesite.

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Age	Simplified Map Unit (Symbol) *Overview Sheet 1*	Map Unit (Symbol) *Colored if present on Overview Sheet 2*	Geologic Description	Geologic Issues	Geologic Features, Processes and General Location	Geologic History
QUARTERNARY	Cenozoic Volcanic Rocks (QTvl)	Andesite of Devils Postpile (Qad)	Light- to dark-gray andesite. Commonly porphyritic with phenocrysts of plagioclase and olivine; rarely vesicular.	None—This unit lies outside of the park boundaries.	**Volcanic Bedrock**—The unit contains well-developed columnar jointing. Exposed in the Devils Postpile quadrangle, southeast of the park.	**Tension, Uplift, and Ice**—Remnants of Pleistocene volcanism.
NEOGENE (Pliocene)	Cenozoic Volcanic Rocks (QTvl)	Hypabyssal rocks (Tda)	Undifferentiated unit of igneous rock. The source map does not provide a detailed description.	None Documented—Limited areal extent.	**Volcanic Bedrock**—Isolated pockets with limited areal extent in the Tuolumne Meadows and Mono Craters quadrangles.	**Tension, Uplift, and Ice**— "Hypabyssal" refers to an igneous body of rock that formed at a shallow depth.
NEOGENE (Pliocene)	Cenozoic Volcanic Rocks (QTvl)	Mafic phonolite (Tmp)	Mafic phonolite (extrusive igneous rock with abundant alkali feldspar) with phenocrysts of phlogopite and olivine in a groundmass with abundant sanidine and leucite.	None Documented—Limited areal extent.	**Volcanic Bedrock**—Limited to massive to platy flows near Merced Pass in the park, Merced Peak quadrangle. Also present outside the park along Grizzly Creek and the West Fork of Granite Creek.	**Tension, Uplift, and Ice**—Lava flows.
NEOGENE (Pliocene)	Cenozoic Volcanic Rocks (QTvl)	Mafic phonolite, ultrapotassic (Tpp)	Ultrapotassic lava. The source map does not provide a detailed description.	None—These units lie outside of the park boundaries.	**Volcanic Bedrock**—Isolated exposures in the Merced Peak quadrangle.	**Tension, Uplift, and Ice**—Lava that solidified in a volcanic neck near the junction of Madera Creek and the West Fork of Granite Creek and a small volcanic pipe near Cold Springs Meadow.
NEOGENE (Pliocene)	Cenozoic Volcanic Rocks (QTvl)	Quartz latite of Two Teats (Tqt)	Fine-grained volcanic equivalent of quartz monzonite containing 5–20% quartz and approximately equal amounts of plagioclase and potassium feldspar.	None—These units lie outside of the park boundaries.	**Volcanic Bedrock**—Exposed in the Mono Craters quadrangle, east of the park.	**Tension, Uplift, and Ice**—Remnants of Neogene volcanism.
NEOGENE (Pliocene)	Cenozoic Volcanic Rocks (QTvl)	Andesite of Deadman Pass (Tadp)	Series of interbedded andesitic flows, cinders, and rubble. Flow rock is commonly vesicular; essentially non porphyritic.	None—These units lie outside of the park boundaries.	**Volcanic Bedrock**—Exposed in the Devils Postpile quadrangle, southeast of the park.	**Tension, Uplift, and Ice**—The unit includes scattered remnants of andesitic rock not necessarily from the same source, but of approximately the same age.
NEOGENE (Pliocene)	Cenozoic Volcanic Rocks (QTvl)	Trachyandesite (Tan, Ttc)	**Tan**: lava flows containing up to 8% potassium oxide. **Ttc**: trachyandesite and trachyte (alkali-rich) cinder cones.	None—These units lie outside of the park boundaries.	**Volcanic Bedrock**—**Tan**: exposed in the Bass Lake quadrangle, south of the park. **Ttc**: exposed near Post Peak, Merced Peak quadrangle.	**Tension, Uplift, and Ice**—Remnants of Neogene volcanism.
NEOGENE (Pliocene)	Cenozoic Volcanic Rocks (QTvl)	Trachybasalt (Ttb)	Light- to dark-gray, fine-grained volcanic rock with abundant olivine phenocrysts. Distinctly alkali (contains abundant sodium and/or potassium).	None—These units lie outside of the park boundaries.	**Volcanic Bedrock**—Exposed in volcanic necks. Exposed south of the park along Granite Creek.	**Tension, Uplift, and Ice**—May represent basalt magma mixed with granitic rock. Potassium-argon isotopic age about 3.3–3.8 million years (Pliocene).
NEOGENE (Miocene)	Cenozoic Volcanic Rocks (QTvl)	Disaster Peak Formation (Tdp)	Medium- to light-gray andesitic lahars with local interbedded stream deposits. Contains rounded to angular pebbles of andesite and basalt in a matrix of volcanic sand-sized particles. Contains conspicuous individual laths and clots of hornblende.	None—These units lie outside of the park boundaries.	**Volcanic Bedrock**—Exposed west and northwest of the park.	**Tension, Uplift, and Ice**—Lahars are volcanic mudflows that flow down the flanks of volcanoes.
NEOGENE (Miocene)	Cenozoic Volcanic Rocks (QTvl)	Trachybasalt plug (Tbo)	Black, basalt plug of limited areal extent known as the Little Devils Postpile. Considered by some to be trachyandesite because it contains more silicon, potassium, and sodium than does basalt.	None	**Volcanic Bedrock**—Excellent columnar jointing in Little Devils Postpile. Located northwest of Tuolumne Meadows along the Tuolumne River, Tuolumne Meadows quadrangle.	**Tension, Uplift, and Ice**—Remnants of a conduit that fed magma to a volcano about 8–9 million years ago (Miocene).

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Age	Simplified Map Unit (Symbol) *Overview Sheet 1*	Map Unit (Symbol) *Colored if present on Overview Sheet 2*	Geologic Description	Geologic Issues	Geologic Features, Processes and General Location	Geologic History
NEOGENE (Miocene)	Cenozoic Volcanic Rocks (QTvl)	Olivine basalt (Tb)	Dark-gray to brownish-black, hard, dense, fresh olivine basalt with microphenocrysts of olivine and sodic bytownite.	None—These units lie outside of the park boundaries.	**Volcanic Bedrock**—Isolated outcrop north of the park in the Matterhorn Peak quadrangle.	**Tension, Uplift, and Ice**—Occurs as lava flows and igneous dikes.
		Volcanic rocks of Hunewill Hills: Basalt (Thb)	Brownish-black to dark-brownish, slightly vesicular, porphyritic basalt. Contains phenocrysts of olivine enclosed within a fine-grained, dense groundmass of labradorite (plagioclase feldspar group), pyroxene, and olivine minerals.		**Volcanic Bedrock**—**Thah** is the primary rock type. Other units have limited areal extent. Exposed in the Matterhorn Peak quadrangle, northeast of the park.	**Tension, Uplift, and Ice**—Occurs as volcanic lava flows in the Hunewill Hills.
		Volcanic rocks of Hunewill Hills: Dacite (Thd)	Dull pinkish-gray, weakly mottled, porphyritic. Contains phenocrysts of andesine, quartz, dark green pyroxene, and black biotite.			
		Volcanic rocks of Hunewill Hills: Andesite (Thah)	Light- to dark-gray, locally brownish, dense, porphyritic andesite. Contains phenocrysts of black hornblende and glassy white andesine. Includes interflow layers of andesitic tuff breccia (**Tht**).			
		Volcanic rocks of Hunewill Hills: Tuff breccia (Tht)	Volcanic tuff breccia of andesitic composition.			
		Stanislaus Group: Eureka Valley tuff (Tsgev)	Tollhouse Flat Member consisting of biotite-bearing, latite tuff. A lower unit consists of densely to moderately welded tuff. A locally exposed upper unit consists of poorly welded to nonwelded tuff.		**Volcanic Bedrock**—Exposed primarily on the south side of Dodge Ridge and south and east of Coyote Meadows in the Pinecrest quadrangle, northwest of the park.	**Tension, Uplift, and Ice**—Potassium-argon isotopic age is about 9.5 million years (Miocene).
		Stanislaus Group: Table Mountain latite (Tsgtm)	Dark-gray to black porphyritic latite with platy plagioclase phenocrysts. Phenocrysts usually have strong tabular orientation.		**Volcanic Bedrock**—Isolated exposure of limited areal extent on the ridge crest northeast of Cooper Pocket, Pinecrest quadrangle, northwest of the park.	**Tension, Uplift, and Ice**—Potassium-argon isotopic age is about 9.2 million years (Miocene).
		Relief Peak Formation (Trp)	Brown to medium-gray andesitic lahars (mudflows) with local interbedded stream deposits. Contains porphyritic volcanic clasts and granitic rocks in a matrix of volcanic sand-sized particles.		**Volcanic Bedrock**—Underlies the Table Mountain latite, north of the park.	**Tension, Uplift, and Ice**—Volcanic mudflows underlie the Table Mountain latite, so they were deposited over 9.2 million years ago (Miocene).
		Andesite of Walker River (Twa)	Light- to medium-gray and pinkish-gray, platy, well-banded porphyritic andesite ranging from hornblende- to biotite-rich. Phenocrysts of hornblende and biotite.		**Volcanic Bedrock**—Exposed in the Matterhorn Peak quadrangle, northeast of the park.	**Tension, Uplift, and Ice**—Evidence of volcanic activity.
		Tuff and tuff breccias of Hanna Mtn. (Tt)	Light- to dark-gray and locally buff-colored, usually well-indurated, massive, poorly layered tuff and tuff breccia. Abundant andesitic and some basaltic debris are set in a fine-grained matrix of volcanic ash and mineral and rock fragments.		**Volcanic Bedrock**—Exposed in the Matterhorn Peak quadrangle.	**Tension, Uplift, and Ice**—Evidence of volcanic activity.

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Age	Simplified Map Unit (Symbol) *Overview Sheet 1*	Map Unit (Symbol) *Colored if present on Overview Sheet 2*	Geologic Description	Geologic Issues	Geologic Features, Processes and General Location	Geologic History
NEOGENE (Miocene)	Cenozoic Volcanic Rocks (QTvl)	Basalt of Brown Bear Pass (Tbb)	Light- to dark-gray, massive basalt. Contains a highly vesicular unit and a purplish brecciated unit,also.	None—This unit lies outside of the park boundaries.	**Volcanic Bedrock**—Vertical columnar jointing. Overlies **Tvs**. Exposed in the Tower Peak quadrangle, north of the park.	**Tension, Uplift, and Ice**—Potassium-argon isotopic ages of 19–20 million years (Miocene).
NEOGENE (Miocene)	Cenozoic Volcanic Rocks (QTvl)	Mehrten Formation (Tmt, Tmf)	**Tmt**: black, dense trachyandesite. **Tmf**: brown volcanic mudflow with rounded cobbles and pebbles of andesite, large granitic boulders, and fragments of **Tmt**.	None Documented—Caps part of the crest and gentle slopes of Rancheria Mountain, north of the steeper slopes above the Grand Canyon of the Tuolumne River.	**Volcanic Bedrock**—**Tmt**: strongly jointed. Exposed in the Hetch Hetchy Reservoir quadrangle.	**Tension, Uplift, and Ice**—Evidence of high-energy mudflows transporting volcanic material downslope.
NEOGENE (Miocene) / PALEOGENE (Oligocene)	Cenozoic Volcanic Rocks (QTvl)	Valley Springs Formation (Tvs)	Rhyolite tuff, partly to densely welded, and bedded ash deposits. Locally includes rhyolitic sedimentary deposits.	None—This unit lies outside of the park boundaries.	**Volcanic Bedrock**—Exposed north of the park in the Tower Peak quadrangle.	**Tension, Uplift, and Ice**—Potassium-argon isotopic ages of 24–27 million years old (Oligocene).

Cretaceous through Triassic Plutonic Rock Units

Age	Simplified Map Unit (Symbol)	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features, Processes and General Location	Geologic History
CRETACEOUS (Upper)	Upper Cretaceous Intrusive Rocks (Kib)	Aplite and Pegmatite (Kapp)	Fine grained, white aplite dikes and sills with minor widely dispersed euhedral crystals of biotite and hornblende. Pegmatite dikes and small masses.	None Significant—Linear exposure of limited areal extent. Limited potential for geologic issues.	Occurs as dikes and sills in the Half Dome granodiorite.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
CRETACEOUS (Upper)	Tuolumne Intrusive Suite (Ktu)	Johnson Granite Porphyry (Kjp)	Light-colored, fine-grained granite that locally contains potassium-feldspar phenocrysts set in a fine-grained groundmass as well as megacrysts of orthoclase and rounded reddish blobs of **Kcp**. Texture ranges from aplite to pegmatite. Forms the core of the Tuolumne Intrusive Suite and thin, aplite dikes marginal to the central mass.	**Rockfalls**—Primarily exposed north and south of Johnson Peak, where it may be prone to rockfall on steeper slopes.	**Granitic Bedrock**—Exposed around Tuolumne Meadows Campground.	**Rise of the Batholith**—Intrudes the Cathedral Peak Granodiorite. Textures suggest that **Kjp** may have been associated with an explosive volcanic event.
CRETACEOUS (Upper)	Tuolumne Intrusive Suite (Ktu)	Cathedral Peak Granodiorite (Kcp)	Medium-grained coarsely porphyritic hornblende-biotite granodiorite with conspicuous megacrysts of potassium-feldspar. Megacrysts are largest and most abundant in the margins of the body and are progressively less abundant and smaller inward. Orthoclase megacrysts are typically 8–10 cm (3–4 in) long and make up about 25% of the rock. Foliation in the rock is generally weak.	**Protection of Glacial Features**—Glacial polish, striations, and other glacial features present on domes composed of **Kcp** at Tuolumne Meadows. **Rockfalls**—Potential rockfall on steeper slopes.	**Granitic Bedrock**—Includes Fairview and Pothole domes. **Dikes**—A notable climbing route is the "Dike Route" on Pywiack Dome near Tenaya Lake. **Megacrysts**—Notable climbing include the "Southeast Buttress" and "Bachar-Yerian Route" on Medlicott Dome near Tuolumne Meadows.	**Rise of the Batholith**—Large crystals in **Kcp** indicate that the magma body must have cooled very slowly over millions of years. A Uranium-lead zircon age of about 88 million years was obtained from the rock.

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Age	Simplified Map Unit (Symbol) *Overview Sheet 1*	Map Unit (Symbol) *Colored if present on Overview Sheet 2*	Geologic Description	Geologic Issues	Geologic Features, Processes and General Location	Geologic History
CRETACEOUS (Upper)	Tuolumne Intrusive Suite (Ktu)	Half Dome Granodiorite (Khd)	Light-colored, medium- to coarse-grained, massive, equigranular hornblende-biotite granodiorite. Contains large crystals of potassium and plagioclase feldspar, biotite, hornblende, and honey-colored sphene up to 10 mm (0.4 in) wide and phenocrysts of potassium feldspar up to 3 cm (1.2 in) wide. Spaces between these crystals are filled by quartz. May be divided into: 1) a porphyritic phase (**Khdp**) with potassium-feldspar megacrysts commonly slightly more than 1 cm (0.4 in) wide and 2–3 cm (0.8–1.2 in) long, and 2) a medium-grained equigranular phase (**Khde**) characterized by euhedral hornblende prisms 1–3 cm (0.4–1.2 in) long, biotite books up to 1 cm (0.4 in) wide, and conspicuous sphene.	**Rockfalls**—Previous rockfalls from Ahwiyah Point have buried part of the Mirror Lake Loop Trail and damaged the Ahwahnee Hotel.	**Granitic Bedrock**—Forms Half Dome and the sheer cliffs between the Ahwahnee Hotel and Mirror Lake. Good exposures at Olmsted Point and along the trail to Vernal and Nevada falls. **Splitter cracks—**A notable climbing route is "Sons of Yesterday" near Royal Arches beneath North Dome. **Flakes—**A notable climbing route is "Hermaphrodite Flake" on Stately Pleasure Dome above Tenaya Lake. **Dihedrals—**A notable climbing route is "Great White Book" on Stately Pleasure Dome above Tenaya Lake. **Dikes—**A notable climbing route is "Snake Dike" climb on the southwest face of Half Dome. **Slabs—**Popular slab climbs on the Glacier Point Apron include "Marginal," "Goodrich Pinnacle," and "The Cow". **Joints—**Exfoliation joints are the primary joint type responsible for the famous landmark Half Dome.	**Rise of the Batholith**—**Khd** is the youngest plutonic rock in the Yosemite Valley area with an age of approximately 87–88 million years.
		Granite of Marie Lakes (Kma)	Light-gray, fine-grained biotite granite.	None Significant—Dikes (linear features) pose little potential for significant geologic issues in the park.	**Granitic Bedrock**—Exposed in dikes near Marie Lakes and on the south slopes of Mounts Lyell and Maclure the Merced Peak quadrangle.	**Rise of the Batholith**—May be correlative with Half Dome Granodiorite.
		Granodiorite of Grayling Lake (Kgrl)	Fine- to medium-grained, well-foliated biotite-hornblende granodiorite. Contains 20–25% small anhedral (lacking well-developed crystal faces) grains of biotite and hornblende and relatively abundant sphene.	None Significant—Limited areal extent on relatively gentle slopes. Little potential for significant geologic issues.	**Granitic Bedrock**—Exposed along the west side of the Clark Range in the Merced Peak quadrangle.	**Rise of the Batholith**—Part of the igneous intrusions related to the Tuolumne Intrusive Suite.
		Granodiorite of Glacier Point (Kglp)	Dark, medium-grained, equigranular well-foliated granodiorite, tonalite, and quartz diorite containing abundant small dark inclusions. Typically contains 15–25% subequal biotite and hornblende. Biotite and hornblende may occur as anhedral grains or in clusters 1–5 mm (0.04–0.2 in) wide. Some grains contain augite.	**Rockfalls**—Rockfalls in 2008 impacted the historic Curry Village area.	**Granitic Bedrock**—Forms a band west of the Half Dome Granodiorite in the Yosemite quadrangle. **Splitter Cracks**—A notable climb is "The Grack" below Glacier Point.	**Rise of the Batholith**—Equivalent to part of the Sentinel Granodiorite (**Ks**) and the Granodiorite of Kuna Crest (**Kkc**). Potassium-argon and rubidium-strontium isotopic ages from a Washburn Point sample were about 92 million years.
		Tonalite of Glen Aulin (Kgla)	Dark-colored rock of variable composition ranging from fine-grained quartz diorite in the west to medium-grained granodiorite at the eastern contact with **Khd** and **Kcp**.	**Rockfalls**—Potential issues for areas north and south of the Glen Aulin High Sierra Camp, but relatively gentle slopes near the camp.	**Granitic Bedrock**—Exposed in the Tuolumne Meadows quadrangle.	**Rise of the Batholith**—Uranium-lead zircon age of about 86 million years.
		Granodiorite of Kuna Crest (Kkc)	Dark-colored, medium-grained, hornblende-biotite granodiorite. Crystals are smaller and biotite and hornblende more abundant than in some other granitic rocks in the park. May contain 20–25% anhedral biotite and hornblende. Contains abundant dark phenocrysts of plagioclase and biotite.	**Rockfalls**—Potential on steeper slopes. Exposed near Tioga Pass but well away from the road. Exposures primarily in the backcountry.	**Granitic Bedrock**—Forms the margin of the Tuolumne Intrusive Suite. The unit consists of gray dikes and small intrusive masses with abundant dark phenocrysts on Mt. Lyell, Mt. Maclure, Rodger Peak, and Electra Peak.	**Rise of the Batholith**—The oldest unit in the suite, **Kkc** gains its dark color from biotite and hornblende, which crystallize from magma before quartz and feldspar. Approximately 91 million years old.
		Sentinel Granodiorite (Ks)	Light-colored, medium-grained, equigranular granodiorite and less abundant tonalite, quartz diorite, and granite. Contains inclusions of El Capitan Granite (**Kec**). Hornblende, biotite, and sphene 2–5 mm (0.08–0.2 in) wide.	**Rockfalls**—From extensive sheet (exfoliation) jointing. Rockfall in 1980 was triggered by an earthquake.	**Granitic Bedrock—**Main mass crosses Yosemite Valley near Sentinel Rock. **Joints—**Exfoliation joints are present.	**Rise of the Batholith**—Dikes of **Ks** cut inclusions of El Capitan Granite, indicating it is younger than **Kec**. Approximate age is about 94 million years.

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CRETACEOUS (Upper)	Tuolumne Intrusive Suite (Ktu)	Yosemite Creek Granodiorite (Kyc)	Predominantly dark-gray, coarse-grained biotite-hornblende quartz diorite that grades to granodiorite. Locally porphyritic with abundant parallel, tabular, plagioclase phenocrysts. Includes about 15% biotite, hornblende, and sphene. Strongly foliated.	**Rockfalls**—Due to extensive sheet jointing.	**Granitic Bedrock—**Included in a myriad of dikes north of Mt. Hoffmann and crops out in a thin band between **Ks** and **Kglp** southeast of Illilouette Ridge. **Joints—**Exfoliation joints are present.	**Rise of the Batholith**—May be used to study the origin of exfoliation joints and their ability to trigger rockfall.
	Upper Cretaceous Intrusive Rocks (Kib)	Granodiorite of Mono Dome (Kmd)	Light- to medium-gray, medium- to coarse-grained, equigranular biotite-hornblende granodiorite; grades locally into biotite granite. Contains pyroxene as discrete crystals and as cores in hornblende.	None—These units lie outside of the park boundaries.	**Granitic Bedrock—**Exposed east of the park.	**Rise of the Batholith**—Potassium-argon isotopic ages are about 85 million years. Rubidium-strontium whole-rock age is about 93 million years.
		Granodiorite of Tioga Lake (Kti)	Medium-grained dark-gray rock. Angular plagioclase and ragged, partly chloritized amphibole crystals are set in a matrix of fine-grained potassium-feldspar, quartz, plagioclase, and biotite.		**Granitic Bedrock—**Exposed north of Tioga Lake in the Tuolumne Meadows quadrangle.	**Rise of the Batholith**—Intrusive igneous rock bodies that join with others to form the impressive Sierra Nevada Batholith.
		Quartz monzonite of Ellery Lake (Kell)	The source map does not provide a detailed description.		Exposed east of the park in the Mono Craters quadrangle.	
		Sheared granodiorite of Koip Crest (Kko)	Granodiorite. The source map does not provide a detailed description.	**Rockfalls**—Limited areal extent. Minor rockfall potential in the backcountry.	**Granitic Bedrock—**Sliver of rock on the western slope of Koip Crest in the Mono Craters quadrangle, eastern border of the park.	**Rise of the Batholith**—Mapped as Cretaceous on the Mono Craters quadrangle but as Jurassic and Triassic metavolcanic hornfels on the Yosemite National Park map of Huber et al. (1989).
	Intrusive Suite of Sonora Pass (Ksp)	Granodiorite of Topaz Lake (Ktz)	Light-gray, coarse-grained biotite granodiorite and granite with roughly equant, well-formed potassium feldspar phenocrysts making up 2–10% of the rock. Quartz typically occurs in 0.5-cm (0.2-in) clots. Mafic mineral content about 10%.	None—These units lie outside of the park boundaries.	**Granitic Bedrock—**Exposed north of the park. Schlieren—Asymmetric schlieren (tabular or disc-like concentrations of minerals in flow layers) locally abundant.	**Rise of the Batholith**—Rubidium-strontium isotopic age of about 87 million years.
		Granodiorite of Kinney Lakes (Kkl)	Medium-grained, equigranular hornblende-biotite granodiorite.		**Granitic Bedrock—**Exposed north of the park.	**Rise of the Batholith**—Rubidium-strontium isotopic age of about 90 million years.
	Upper Cretaceous Intrusive Rocks (Kib)	Felsic Granitic Rocks (Kfgr)	Biotite leucogranite and aplite. Includes trondhjemite in the east- and south-central parts of the Lake Eleanor quadrangle.	None Significant—Isolated exposures of limited areal extent.	**Granitic Bedrock—**Exposed in the Lake Eleanor quadrangle.	**Rise of the Batholith**—Some of the last minerals to crystallize in the evolution of a pluton.
	John Muir Intrusive Suite (Kjm)	Granodiorite of Cow Meadow (Kcm)	Fine- to medium-grained rock that has intruded into **Kmg**.	None—These units lie outside of the park boundaries.	**Granitic Bedrock—**Exposed southeast of the park in the Kaiser Peak quadrangle.	**Rise of the Batholith**—Age relative to Granodiorite of Lake Edison (**Kle**) is unknown.
		Granodiorite of Lake Edison (Kle)	Equigranular, medium-grained granodiorite. Foliated in margins but structureless in core. Typically contains abundant sphene.			**Rise of the Batholith**—Intrudes **Kmg** and older plutons. Age relative to **Kcm** and to fine- to medium-grained quartz monzonite and granodiorite is unknown.

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CRETACEOUS (Upper)	John Muir Intrusive Suite (Kjm)	Mount Givens Granodiorite (Kmg)	Biotite-hornblende granodiorite and porphyritic biotite granodiorite.	None—These units lie outside of the park boundaries.	**Granitic Bedrock**—Forms the northern margin of one of the largest plutons in the Sierra Nevada Batholith. Exposed southeast of the park.	**Rise of the Batholith**—Potassium-argon isotopic age of 82–87 million years.
	Upper Cretaceous Intrusive Rocks (Kib)	Granodiorite of Soldier Lake pluton (Ksg)	Fine-grained, light-gray, massive, well-jointed, strongly foliated granodiorite. Contains zoned calcic andesine, quartz, biotite, hornblende, and alkali feldspar.	None Significant—Isolated backcountry exposure.	**Granitic Bedrock**—Surrounds Soldier and Spiller lakes, south of Virginia Peak in the northeast section of the park.	**Rise of the Batholith**—One of many igneous intrusions that compose the extensive Sierra Nevada Batholith.
		Rocks of Buckeye Creek pluton (Kbp)	Massive, light- to medium-gray and locally pinkish, porphyritic quartz monzonite composed of quartz, orthoclase, calcic oligoclase, biotite, and hornblende. Potassium feldspar phenocrysts. Grades locally into dark medium-grained hornblende-biotite quartz diorite.	None—This unit lies outside of the park boundaries.	Exposed north of the park.	**Rise of the Batholith**—Part of the Sierra Nevada Batholith.
	Intrusive Suite of Jack Main Canyon (Kjmc)	Granodiorite of Boundary Lake (Kblg)	Light-colored, medium-grained biotite granodiorite and granite characterized by discrete anhedral quartz grains. Locally porphyritic with varying proportions of plagioclase and small tabular potassium-feldspar phenocrysts.	**Rockfall**—Backcountry exposures with rockfall potential on steeper slopes.	**Granitic Bedrock**—Exposed in the northwest section of the park.	**Rise of the Batholith**—Units are thought to have been emplaced at relatively the same time as part of the Jack Main Canyon Intrusive Suite. **Kblg**: Rubidium-strontium age of about 91 million years. **Kgi**: Potassium-argon isotopic ages of about 81–88 million years.
		Granodiorite of Lake Vernon (Klv)	Hornblende-biotite granodiorite characterized by two distinct grain sizes of mafic minerals: 1) scattered grains 0.5–1 cm (0.2–0.4 in) in size, and 2) abundant grains up to 1 mm (0.04 in) in size. The two grain sizes give the rock a spotted appearance. Contains numerous flattened mafic inclusions.		**Granitic Bedrock**—Exposed in the northwest section of the park, Tower Peak quadrangle.	
		Granodiorite of Bearup Lake (Kbu)	Even-grained granodiorite characterized by euhedral hornblende and biotite crystals and a wide range of mafic mineral content.		**Granitic Bedrock**—Exposed in the northwest section of the park, Tower Peak quadrangle.	
		Quartz diorite of Mount Gibson (Kgi)	Dark-gray to black, coarse-grained, hornblende-biotite quartz diorite. Contains pyroxene.		Exposed in the northwest section of the park, Hetch Hetchy Reservoir and Tower Peak quadrangles.	
	Intrusive Suite of Washburn Lake (Kwl)	Granite porphyry of Cony Crags (Kcc)	Biotite granite porphyry in the core of a disrupted compound pluton at the headwaters of the Merced River. Contains sparse phenocrysts of plagioclase, quartz, and potassium feldspar in a fine-grained groundmass.	**Rockfall**—Backcountry exposures with rockfall potential on steeper slopes.	**Granitic Bedrock**—Only exposed in the Cony Crags area in the Merced Peak Quadrangle.	**Rise of the Batholith**—Forms the core of a compound pluton.
		Granite of Turner Lake (Ktl)	Biotite granite and felsic granodiorite containing abundant tabular 1–2-mm (0.04–0.08-in) phenocrysts of potassium feldspar in a medium-grained groundmass.		**Granitic Bedrock**—Exposed in the Merced Peak and Tuolumne Meadows quadrangles.	**Rise of the Batholith**—Part of the intrusive sequence that resulted in the Washburn Lake Intrusive Suite.
		Granodiorite of Red Devil Lake (Krd)	Equigranular granodiorite and granite forming the outer unit of the intrusive suite of Washburn Lake. Ranges from inclusion-rich mafic biotite-hornblende granodiorite at the outer margin to biotite granite at the inner contact with **Ktl**.		**Granitic Bedrock**—More widespread exposures than **Kcc** and **Ktl**. South of Gallison Lake, the granodiorite is strongly sheared.	**Rise of the Batholith**—Forms the outer unit of the intrusive suite of Washburn Lake. Uranium-lead isotopic age of approximately 98 million years.

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CRETACEOUS (Upper)	Upper Cretaceous Intrusive Rocks (Kib)	Granodiorite of Hodgdon Ranch (Khr)	Fine- to medium-grained hornblende-biotite granodiorite with coarse potassium feldspar crystals. Eastern margin is in contact with **Kncc** in the Lake Eleanor quadrangle.	None Significant—Primarily exposed on low-gradient slopes.	**Granitic Bedrock**—Exposed in the Lake Eleanor quadrangle.	**Rise of the Batholith**—Igneous intrusions that form part of the extensive Sierra Nevada Batholith.
CRETACEOUS (Upper)	Upper Cretaceous Intrusive Rocks (Kib)	Tonalite of North Crane Creek (Kncc)	Medium-grained, biotite-hornblende tonalite. Includes a contact breccia zone (**Kccb**).	None Significant—Primarily exposed on low-gradient slopes.	**Granitic Bedrock**—Exposed near the western border of the park in the Lake Eleanor quadrangle.	**Rise of the Batholith**—Igneous intrusions that form part of the extensive Sierra Nevada Batholith.
CRETACEOUS (Upper)	Upper Cretaceous Intrusive Rocks (Kib)	Tonalite of Tamarack Creek (Ktc)	Medium-grained hornblende-biotite tonalite. Sparse but conspicuous euhedral hornblende crystals, 5–10 mm (0.2–0.4 in) long.	None Significant—Primarily exposed on low-gradient slopes.	**Granitic Bedrock**—Exposed in the Lake Eleanor quadrangle.	**Rise of the Batholith**—May be correlative with the granodiorite of Illilouette Creek (**Kic**) in the Merced Peak quadrangle.
CRETACEOUS (Upper)	Intrusive Suite of Buena Vista Crest (Kbv)	Granite of Chilnualna Lakes (Kcl)	Light-colored, fine-grained, equigranular granodiorite containing 5–10% biotite.	**Rockfall**—Isolated exposures on steep slopes. Rockfall potential along the southern margin of Yosemite Valley. **Kcl**: limited areal extent.	**Granitic Bedrock—**Forms a small pluton northwest of Buena Vista Peak in the Yosemite quadrangle.	**Rise of the Batholith**—Units are thought to have been emplaced at relatively the same time as part of the Buena Vista Crest Intrusive Suite. **Khrr**: surrounds **Kcl**. **Kbv**: intrudes, and is thus younger than, nearly all rocks it contacts. **Kol**: Uranium-lead isotopic ages of 107 million years and 112 million years from a sample collected near Ostrander Lake are probably 10–15 million years too old.
CRETACEOUS (Upper)	Intrusive Suite of Buena Vista Crest (Kbv)	Granodiorite of Horse Ridge (Khrr)	Fine-grained, equigranular, calcic granodiorite forming an envelope around the lighter colored **Kcl**. Typically contains 10–15% fine flakes of biotite and about 10% potassium feldspar grains.	**Rockfall**—Isolated exposures on steep slopes. Rockfall potential along the southern margin of Yosemite Valley. **Kcl**: limited areal extent.	**Granitic Bedrock**—Exposed in the Yosemite quadrangle.	**Rise of the Batholith**—Units are thought to have been emplaced at relatively the same time as part of the Buena Vista Crest Intrusive Suite. **Khrr**: surrounds **Kcl**. **Kbv**: intrudes, and is thus younger than, nearly all rocks it contacts. **Kol**: Uranium-lead isotopic ages of 107 million years and 112 million years from a sample collected near Ostrander Lake are probably 10–15 million years too old.
CRETACEOUS (Upper)	Intrusive Suite of Buena Vista Crest (Kbv)	Bridalveil Granodiorite (Kbv)	Bluish-gray, "salt-and-pepper" granodiorite. Typically a sodic (containing sodium) granodiorite containing about 5% biotite in fine shreds, but near external contacts includes calcic (containing calcium) granodiorite containing about 10% biotite and less abundant hornblende. Includes a zone of abundant inclusions.	**Rockfall**—Isolated exposures on steep slopes. Rockfall potential along the southern margin of Yosemite Valley. **Kcl**: limited areal extent.	**Granitic Bedrock**—Forms dikes and gently dipping sheets in the southern wall of Yosemite Valley and several larger bodies farther south. Exposed in the Yosemite quadrangle.	**Rise of the Batholith**—Units are thought to have been emplaced at relatively the same time as part of the Buena Vista Crest Intrusive Suite. **Khrr**: surrounds **Kcl**. **Kbv**: intrudes, and is thus younger than, nearly all rocks it contacts. **Kol**: Uranium-lead isotopic ages of 107 million years and 112 million years from a sample collected near Ostrander Lake are probably 10–15 million years too old.
CRETACEOUS (Upper)	Intrusive Suite of Buena Vista Crest (Kbv)	Granodiorite of Breeze Lake (Kbz)	Light-gray biotite granodiorite with grains of various sizes. Abundant plagioclase phenocrysts up to 8 mm (0.3 in) in length are set in a fine-grained groundmass. Potassium feldspar ranges in different samples from fine interstitial grains to crystals up to 1 cm (0.4 in) wide.	**Rockfall**—Isolated exposures on steep slopes. Rockfall potential along the southern margin of Yosemite Valley. **Kcl**: limited areal extent.	**Granitic Bedrock**—Forms an elongate stock of limited areal extent near Breeze and Chain lakes, southeastern boundary of the park, Merced Peak quadrangle.	**Rise of the Batholith**—Units are thought to have been emplaced at relatively the same time as part of the Buena Vista Crest Intrusive Suite. **Khrr**: surrounds **Kcl**. **Kbv**: intrudes, and is thus younger than, nearly all rocks it contacts. **Kol**: Uranium-lead isotopic ages of 107 million years and 112 million years from a sample collected near Ostrander Lake are probably 10–15 million years too old.
CRETACEOUS (Upper)	Intrusive Suite of Buena Vista Crest (Kbv)	Granodiorite of Ostrander Lake (Kol)	Medium-grained equigranular hornblende-biotite granodiorite and biotite granite. Typically contains 6–10% anhedral biotite and hornblende. Contains about 10% mafic minerals, predominantly biotite in poorly formed grains 1–3 mm (0.04–0.1 in) wide. Locally contains phenocrysts of potassium feldspar.	**Rockfall**—Isolated exposures on steep slopes. Rockfall potential along the southern margin of Yosemite Valley. **Kcl**: limited areal extent.	**Granitic Bedrock**—Exposed in the southern part of the park as a large pluton in the eastern Yosemite quadrangle and western Merced Peak quadrangle.	**Rise of the Batholith**—Units are thought to have been emplaced at relatively the same time as part of the Buena Vista Crest Intrusive Suite. **Khrr**: surrounds **Kcl**. **Kbv**: intrudes, and is thus younger than, nearly all rocks it contacts. **Kol**: Uranium-lead isotopic ages of 107 million years and 112 million years from a sample collected near Ostrander Lake are probably 10–15 million years too old.
CRETACEOUS (Upper)	Intrusive Suite of Buena Vista Crest (Kbv)	Leaning Tower Granite (Klt)	Biotite-hornblende granite and granodiorite. Clusters of biotite and hornblende give the unit a spotted appearance. Biotite is replacing hornblende in some clusters. Sparsely porphyritic with potassium feldspar phenocrysts up to 5 mm (0.2 in).	**Rockfall**—Isolated exposures on steep slopes. Rockfall potential along the southern margin of Yosemite Valley. **Kcl**: limited areal extent.	**Granitic Bedrock—**Forms three small bodies exposed on the walls of Yosemite Valley.	**Rise of the Batholith**—Units are thought to have been emplaced at relatively the same time as part of the Buena Vista Crest Intrusive Suite. **Khrr**: surrounds **Kcl**. **Kbv**: intrudes, and is thus younger than, nearly all rocks it contacts. **Kol**: Uranium-lead isotopic ages of 107 million years and 112 million years from a sample collected near Ostrander Lake are probably 10–15 million years too old.
CRETACEOUS (Upper)	Intrusive Suite of Buena Vista Crest (Kbv)	Granodiorite of Illilouette Creek (Kic)	Medium-grained, equigranular, biotite-hornblende granodiorite and much less abundant granite and tonalite. Up to 20% biotite and hornblende. Includes stout prisms of hornblende up to 1 cm (0.4 in) long. Mafic inclusions and schlieren typically define a foliation. Includes a zone of inclusions (**Kici**).	**Rockfall**—Isolated exposures on steep slopes. Rockfall potential along the southern margin of Yosemite Valley. **Kcl**: limited areal extent.	**Granitic Bedrock**—Yosemite quadrangle: flanks Horse Ridge and extends northwest through Bridalveil Creek Campground. Merced Peak quadrangle: forms the marginal unit of a large compound pluton that extends westward to Bridalveil Creek.	**Rise of the Batholith**—Units are thought to have been emplaced at relatively the same time as part of the Buena Vista Crest Intrusive Suite. **Khrr**: surrounds **Kcl**. **Kbv**: intrudes, and is thus younger than, nearly all rocks it contacts. **Kol**: Uranium-lead isotopic ages of 107 million years and 112 million years from a sample collected near Ostrander Lake are probably 10–15 million years too old.

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Age	Simplified Map Unit (Symbol) *Overview Sheet 1*	Map Unit (Symbol) *Colored if present on Overview Sheet 2*	Geologic Description	Geologic Issues	Geologic Features, Processes and General Location	Geologic History
CRETACEOUS (Upper)	Intrusive Suite of Buena Vista Crest (Kbv)	Quartz diorite of Tamarack Creek (Ktmc)	Dark-gray, coarse-grained biotite-hornblende quartz diorite. Locally foliated. Hornblende crystals are normally short and stubby, but locally more than 1.3 cm (0.5 in) long.	**Rockfall**—Isolated exposures on steep slopes. Rockfall potential along the southern margin of Yosemite Valley. **Ktmc**: limited areal extent.	Limited exposures in the southwestern part of the Hetch Hetchy Reservoir quadrangle.	**Rise of the Batholith**—Units are thought to have been emplaced at relatively the same time as part of the Buena Vista Crest Intrusive Suite. **Ktmc**: Potassium-argon isotopic age of approximately 89–96 million years. **Kid**: dikes cut **Kec** and **Ktg** on the northern wall of Yosemite Valley.
		Quartz diorite (Kid)	Dark, fine- to medium-grained dikes of hornblende quartz diorite to biotite tonalite and mafic biotite granodiorite. Contains about 20% biotite and hornblende.		Quartz diorite	
	Upper Cretaceous Intrusive Rocks (Kib)	Granodiorite of Turner Ridge (Ktr)	Distinctive dark, porphyritic granodiorite and tonalite. Contains conspicuous, corroded, equant phenocrysts of quartz and plagioclase and subhedral grains of biotite and hornblende. Tablets of plagioclase are up to 1 cm (0.4 in) in size.	None—Isolated backcountry exposures, some linear, with limited areal extent covering relatively gentle slopes.	**Granitic Bedrock**—Forms a small pluton and dikes in the Yosemite quadrangle.	**Rise of the Batholith**—The intrusion extends discontinuously from near Bridalveil Creek Campground to the South Fork of the Merced River.
	Intrusive Suite of Merced Peak (Kmp)	Granite of Timber Knob (Ktk)	White to very light gray, fine-grained equigranular biotite leucogranite.	None—These units lie outside of the park boundaries.	**Granitic Bedrock**—Forms a stock and dikes near Timber Knob and the Strawberry Tungsten Mine area of the Merced Peak quadrangle.	**Rise of the Batholith**—Part of the Merced Peak Intrusive Suite.
		Leucogranite of Norris Creek (Kn)	Very fine to medium-grained white leucogranite and aplite.		**Granitic Bedrock**—Forms a plexus of dikes near Jackass Meadow, Merced Peak quadrangle, southeast of the park.	
		Granodiorite of Jackass Lakes (Kjl)	Very light-gray, medium-grained granodiorite containing about 10% biotite and less hornblende. Ranges from tonalite and quartz diorite to porphyritic leucogranite with potassium feldspar phenocrysts. Locally contains abundant inclusions of older metamorphic and plutonic rocks (**Kjli**).	None Significant—In the park, backcountry exposures are located on relatively gentle slopes.	**Granitic Bedrock**—Large pluton underlies much of the southeastern half of the Merced Peak quadrangle, southeast of the park.	**Rise of the Batholith**—Units are thought to have been emplaced at relatively the same time as part of the Merced Peak Intrusive Suite.
	Upper Cretaceous Intrusive Rocks (Kib)	Quartz monzonite of Shellenbarger Lake (Ksl)	Fine- to medium-grained, commonly porphyritic with albite (feldspar) phenocrysts of possible replacement origin.	None—This unit lies outside of the park boundaries.	Exposed in the Devils Postpile quadrangle, southeast of the park.	**Rise of the Batholith**—Part of the extensive Sierra Nevada Batholith.
		Leucogranite of Red Peak (Krp)	Biotite leucogranite porphyry containing phenocrysts of plagioclase and quartz in a fine-grained, sugary-textured groundmass. Very light gray where fresh. Mostly weathered to shades of red and yellow due to alteration of disseminated pyrite.	None Significant—Isolated backcountry exposure near Red Peak. Potential rockfall on steeper slopes, but a relatively insignificant issue considering the location of the exposure.	**Granitic Bedrock**—Some calcic cores of plagioclase have been replaced by potassium feldspar. Contains miarolitic cavities (small irregular holes). Zone of abundant inclusions (**Krpi**). Exposed near Red Peak in the Merced Peak quadrangle.	**Rise of the Batholith**—Secondary minerals may form in miarolitic cavities. Forms part of the Sierra Nevada Batholith.
		Leucogranite of Post Peak (Kpp)	Fine-grained biotite leucogranite porphyry similar to **Krp** but lacking miarolitic cavities and pyrite. Weathers very light-gray. Zone of abundant mafic inclusions (**Kppi**).	None Significant—Isolated exposures with limited areal extent.	**Granitic Bedrock**—Forms small masses along the southeastern border of the park near Triple Divide and Post peaks, Merced Peak quadrangle.	**Rise of the Batholith**—Leucogranites contain few mafic minerals, suggesting that solidification occurred late in the evolution of the magma body.
		Granodiorite of Horsethief Creek (Khc)	Medium-light-gray hornblende-biotite granodiorite porphyry. Contains very abundant phenocrysts, predominantly plagioclase, in a fine-grained sugary-textured groundmass.	None—This unit lies outside of the park boundaries.	**Granitic Bedrock**—Forms a small mass along the South Fork of the Merced River east of Moraine Meadow, Merced Peak quadrangle.	**Rise of the Batholith**—Localized igneous intrusions forming part of the extensive Sierra Nevada Batholith.

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CRETACEOUS (Upper)	Upper Cretaceous Intrusive Rocks (Kib)	Granite of Grace Meadow (Kgm)	Light-pink to white, sugary, medium- to fine-grained alaskite with rare dark minerals. Contains abundant inclusions of diorite, gabbro, quartzite, biotite schist, and marble.	**Rockfall**—Isolated backcountry location with few steep slopes. Potential rockfall but no significant issues for the park.	**Granitic Bedrock**—Exposed near the northern border of the park in the Tower Peak quadrangle.	**Rise of the Batholith**—Forms part of the extensive Sierra Nevada Batholith.
		Microgabbro of the Clark Range (Kcr)	Medium-gray microgabbro (fine-grained). Contains sparse tabular phenocrysts of plagioclase and clots of hornblende in a fine-grained groundmass.	None Significant—Linear exposure with limited areal extent.	Forms a 2–8-m (7–26 ft)- wide dike that extends from the east flank of Mount Clark to the Red Peak Fork of the Merced River, Merced Peak quadrangle.	**Rise of the Batholith**—Dikes are features that are younger than the rocks into which they intrude.
		Granodiorite of Grizzly Creek (Kgc)	Mafic hornblende-biotite granodiorite and tonalite west of Quartz Mountain. Contains abundant tabular phenocrysts of plagioclase and conspicuous corroded phenocrysts of quartz.	None—This unit lies outside of the park boundaries.	**Granitic Bedrock—**Distinct unit forms the north end of an elongate northeast-trending pluton cutting the leucogranite of Shuteye Peak, south of the park.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
		Quartz diorite of Aspen Valley (Kav)	Medium-grained biotite-hornblende tonalite to quartz diorite. Contains mafic minerals. Locally sheared. Locally divided into a fine-grained hornblende-biotite quartz diorite unit (**Kavt**).	None—Exposures in Aspen Valley are located on relatively gentle topography and do not pose a significant risk for rockfall in the park.	Where sheared, the unit is more felsic than elsewhere. Exposed in the western part of the park, Lake Eleanor quadrangle.	**Rise of the Batholith**—Probably correlative with the tonalite of Poopenaut Valley (**Kpv**).
		Granite of Piute Mountain (Kpm)	Light-pink to orange, medium- to coarse-grained granite containing abundant, closely packed, tabular microcline (feldspar) crystals.	None Significant—Isolated backcountry exposures with limited areal extent.	**Granitic Bedrock—**Limited exposure around Piute Mountain in the Tower Peak quadrangle, northern part of the park.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
		Complex of Mahan Peak (Kmp)	Strongly foliated and migmatitic complex of fine-grained leucogranite with abundant diorite inclusions and cut by unfoliated, fine-grained granitic dikes and irregular masses.	**Rockfall**—Backcountry exposures with rockfall potential on steeper slopes.	**Granitic Bedrock—**Northwest-trending exposure in the western part of the Tower Peak quadrangle, northern part of the park.	**Rise of the Batholith**—Considered to be equivalent to part of Granodiorite of Double Rock (**Kdr**), which may be Early Cretaceous in age.
		Granite of Avonelle Lake (Kavl)	Coarse-grained biotite granite, commonly with abundant tabular phenocrysts of microcline with maximum dimensions of 3 cm (1.2 in).		**Granitic Bedrock—**Extensive northwest-trending exposure in the Tower Peak quadrangle, northern part of the park.	**Rise of the Batholith**—Considered to be equivalent to Granodiorite of Rancheria Mountain (**Krm**) and part of Granodiorite of Double Rock (**Kdr**), both of which may be Early Cretaceous in age.
		Granodiorite of Fremont Lake (Kfl)	Medium-dark-gray, medium-grained, hornblende-biotite granodiorite. Where hornblende-rich, contains abundant lenticular or elongate mafic inclusions, locally in clusters.	**Rockfall**—Backcountry exposures with limited areal extent in the park. Potential rockfall on steeper slopes south of Twin Lakes.	**Granitic Bedrock—**Primarily exposed north of the park but crosses the border near Twin Lakes, Tower Peak quadrangle. Mostly mafic free and more granitic in the southwestern part of its exposure.	**Rise of the Batholith**—The unit extends west into the Pinecrest quadrangle where it is equivalent to the Granodiorite of Kinney Lakes (**Kkl**).
		Granodiorite of Long Canyon (Kloc)	Dark hornblende-biotite granodiorite and quartz-diorite with about 30% mafic mineral content and abundant mafic inclusions.	None—This unit lies outside of the park boundaries.	**Granitic Bedrock—**Exposed north of the park in the Tower Peak quadrangle.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
		Granodiorite North of Tuolumne Peak (Ktp)	Small masses and dikes of hornblende-biotite granodiorite.	None Significant—Isolated exposures with limited areal extent.	**Granitic Bedrock—**Exposed in the Tuolumne Peak quadrangle.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.

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CRETACEOUS (Upper)	Intrusive Suite of Yosemite Valley (Kyv)	Taft Granite (Ktg)	Light-colored, medium-grained, equigranular leucogranite. Weathers yellowish gray. Similar to **Kec** but is finer-grained and lacks phenocrysts.	**Rockfall**—Isolated exposures on steep slopes. Rockfall potential along the margins of Yosemite Valley.	**Granitic Bedrock**—Forms several small masses cutting **Kec** and extending south from El Capitan and Taft Point. Forms the brow of El Capitan. Exposed in the Yosemite quadrangle. **Dikes**	**Rise of the Batholith**—A uranium-lead isotopic age of 96 million years is probably too young.
CRETACEOUS (Upper) / CRETACEOUS (Lower)		Leucogranite of Ten Lakes (Ktnl)	White, coarse-grained leucogranite mottled by gray anhedral quartz crystals. Quartz, microcline, and plagioclase in equal proportions; about 4% mafic mineral content.	**Rockfall**—Backcountry exposures with rockfall potential on steeper slopes.	**Granitic Bedrock**—Exposed in the northern part of the park in the Hetch Hetchy Reservoir, Tower Peak, and Tuolumne Meadows quadrangles.	**Rise of the Batholith**—Rubidium-strontium whole-rock age of 98 million years.
CRETACEOUS (Lower)		Granite of Rancheria Mountain (Krm)	Coarse-grained biotite granite and quartz monzonite. Commonly contains blocky phenocrysts of potassium feldspar. Evenly disseminated, fine- to medium-grained, anhedral biotite flakes. Phenocrysts of microcline are locally abundant.		**Granitic Bedrock**—Exposed in the Hetch Hetchy Reservoir and Lake Eleanor quadrangles.	**Rise of the Batholith**—May be correlative with **Ktg**.
		El Capitan Granite (Kec)	Light-colored, coarse-grained biotite granodiorite and granite with dark- gray blobs (enclaves) of diorite which contains abundant biotite. Weathers yellowish gray- to pinkish- gray. Coarse quartz and potassium feldspar crystals stand out on the surface. Dark quartz grains are as large as 1 cm (0.4 in) and potassium feldspar tablets may be 1.3 cm (0.5 in) in length. Biotite is the primary mafic mineral. Sparse hornblende. May be divided into: 1) granodiorite facies (**Keca**), 2) quartz monzonoite facies (**Kecb**), 3) quartz rich granodiorite facies (**Kecc**), and quartz rich quartz monzonite (**Kecd**).	**Rockfall**—Previous rockfalls have threatened visitor safety and damaged park infrastructure. The Cookie Cliff rockslide of 1982, for example, blocked the El Portal Road, severed sewage lines, and destroyed the telephone line.	**Granitic Bedrock**—Forms El Capitan and coarsely-jointed rock masses. Contains exfoliation joints. **Splitter Cracks—**A notable climbing route is “Reed’s Pinnacle Direct” above the Big Oak Flat Road. **Flakes—**Notable climbing routes include “Boot Flake” and “Texas Flake” on the nose route of El Capitan, and “Wheat Thin” on Cookie Cliff. **Dihedrals—**A notable climbing route is “Five Open Books” west of Lower Yosemite Fall. **Dikes**—Dark, fine-grained diorite dikes cut across El Capitan granite. **Chickenheads—**Notable climbs can be found along the western exposures of El Capitan and include “Sloth Wall,” “Boneheads,” and “Fun Terminal” in Merced Gorge.	**Rise of the Batholith**—Enclaves may have formed when a second, darker (basaltic) magma mixed with the granitic magma, broke apart, and dispersed throughout the lighter granite. Uranium-lead isotopic age of a sample from Turtleback Dome is 103 million years.
		Granite of Big Creek (Kbc)	Light-colored, medium-grained, equigranular biotite granite and leucogranite, similar to **Ktg**. Contains about 5% biotite and opaque minerals in 1–2-mm (0.04–0.08-in) grains.	None Significant—Backcountry exposures on relatively gentle slopes.	**Granitic Bedrock**—Forms a small pluton intrusion into Bass Lake Tonalite (**Kblt**) at the southern margin of the Yosemite quadrangle.	**Rise of the Batholith**—Granitic rocks of the Yosemite Valley Intrusive Suite that form part of the extensive Sierra Nevada Batholith.
		Granodiorite of Double Rock (Kdr)	Gray, coarse-grained, porphyritic biotite granodiorite. Weathers buff or reddish- brown. Locally abundant lensoid mafic inclusions accompanied by aligned tabular potassium-feldspar phenocrysts give the granodiorite a streaked appearance.	**Rockfall**—Backcountry exposures on relatively gentle and steep slopes. Rockfall potential on the slopes of Regulation and Petit peaks.	**Granitic Bedrock**—Exposed in the Hetch Hetchy Reservoir and Tuolumne Meadows quadrangles.	
		Granodiorite of Mount Hoffman (Kmh)	Light-gray, coarse-grained biotite granodiorite. Locally porphyritic. Weathers buff or reddish brown.	**Rockfall**—Potential rockfall on the slopes of Mount Hoffman.	**Granitic Bedrock**—Mount Huffman pluton. The southeastern border of the pluton is locally sheared. Exposed in the Hetch Hetchy Reservoir and Tuolumne Meadows quadrangles.	**Rise of the Batholith**—Rubidium-strontium whole-rock age of approximately 98 million years.

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CRETACEOUS (Lower)	Intrusive Suite of Yosemite Valley (Kyv)	Granite of Gray Peak (Kgp)	Hornblende-biotite granite. Contains prominent tabular phenocrysts of potassium feldspar up to 3 cm (1.2 in) long in a coarse-grained groundmass. Much of the rock is strongly sheared.	**Rockfall**—Isolated backcountry exposure. Although a potential rockfall hazard on the slopes of Gray Peak, the unit is probably not a major geologic issue for the park.	**Granitic Bedrock**—Underlies the north slope of Gray Peak in the Clark Range. Exposed in the Merced Peak quadrangle.	**Rise of the Batholith**—Granitic rocks of the Yosemite Valley Intrusive Suite that form part of the extensive Sierra Nevada Batholith.
		Granite of Bald Mountain (Kbam)	Medium- to coarse-grained granite, similar to **Krm**. Locally highly sheared.	**Rockfall**—Exposures with rockfall potential on the slopes of Bald Mountain and slopes adjacent to the Tuolumne River. Exposures near buildings are on gentler slopes.	**Granitic Bedrock**—Exposed in the western part of the park in the Lake Eleanor quadrangle.	
		Granite of Swamp Lake (Kswl)	Medium- to coarse-grained granite and granodiorite, similar to **Krm**.	**Rockfall**—Exposures surrounding Swamp Lake are on gentle topography. Steeper south-facing slopes may have rockfall potential into Poopenaut Valley.	**Granitic Bedrock**—Exposed west of Hetch Hetchy Reservoir in the Lake Eleanor quadrangle.	
	Lower Cretaceous Intrusive Rocks (Kia)	Granodiorite of Beasore Meadow (Kbe)	Medium-grained hornblende-biotite granodiorite. Locally contains large swarms of abundant mafic inclusions. Intrudes **Ksp**.	None—These units lie outside of the park boundaries.	**Granitic Bedrock**—Exposed south of the park in the Shuteye Peak quadrangle.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
	Shaver Intrusive Suite (KJsh)	Granite of Shuteye Peak (Ksp)	Very light-gray leucogranite and biotite granite containing sparse to abundant tabular phenocrysts of potassium feldspar up to 1 cm (0.4 in) long. Much of the rock is strongly sheared.	None—These units lie outside of the park boundaries.	**Granitic Bedrock**—Forms the north end of a large pluton that extends 50 km (30 mi) south of the park.	
		Granite of Stovepipe Campground (Ksc)	Light-colored, medium-grained, biotite granite with tabular phenocrysts of potassium feldspar. Contains 2–9% mafic minerals, primarily biotite.		**Granitic Bedrock**—Forms a small pluton in the southwestern corner of the Yosemite quadrangle, west of the park.	**Rise of the Batholith**—Composition and texture of **Ksc** is similar to **Ksp**, suggesting that the two units are correlative.
	Lower Cretaceous Intrusive Rocks (Kia)	Granodiorite of Bummers Flat (Kbf)	Porphyritic biotite granodiorite with potassium-feldspar phenocrysts commonly averaging about 2 cm (0.8 in) in length.	None—These units lie outside of the park boundaries.	**Granitic Bedrock**—Exposed northwest of the park.	**Rise of the Batholith**—Preliminary Rubidium-strontium data indicate an age of about 101 million years.
		Granite of Upper Twin Lake (Kut)	Pink, coarse-grained, equigranular biotite granite. Locally has a very strong vertical lineation, probably of metamorphic origin.	None Significant—Backcountry exposures with limited areal extent. Rockfall potential on steeper slopes but no significant issue to the park.	**Granitic Bedrock**—Limited areal exposure along the northern border of the park, Tower Peak quadrangle.	**Rise of the Batholith**—The lineation may be of metamorphic origin.
		Granite of Bond Pass (Kbop)	Gray hornblende-biotite granite and granodiorite with moderately large, pink potassium-feldspar phenocrysts. Locally intensely sheared. Includes bodies of aplite or fine-grained sugary alaskite containing tourmaline rosettes.	**Rockfall**—Isolated backcountry exposures with rockfall potential on steeper slopes from Forsyth Peak south to Craig Peak.	**Granitic Bedrock**—Exposed along the northern border of the park in the Tower Peak quadrangle.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
		Aplite North of Bernice Lake (Kabl)	Aplite. The source map does not provide a detailed description.	None Significant—Limited areal exposure. Low potential for geologic issues	Limited exposure of aplite north of Bernice Lake in the Tuolumne Meadows quadrangle.	

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CRETACEOUS (Lower)	Lower Cretaceous Intrusive Rocks (Kia)	Granite of Ireland Lake (Kil)	Medium- to coarse-grained porphyritic granite, much of it strongly sheared.	None Significant—Limited areal exposure. Low potential for geologic issues	**Granitic Bedrock**—Limited exposure near Bernice Lake, Tuolumne Meadows quadrangle.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
		Leucogranite of Gallison Lake (Kgl)	Fine-grained felsic granite.		**Granitic Bedrock**—Exposed south of Gallison Lake in the Tuolumne Meadows quadrangle.	
		Granite porphyry of Star Lakes (Kst)	Hornblende granodiorite, granodiorite porphyry, and biotite granite porphyry. Contains abundant phenocrysts of plagioclase in a medium- to fine-grained sugary-textured ground mass.	None Significant—Limited areal extent in the park. Low potential for geologic issues in the park.	**Granitic Bedrock**—Primarily exposed south of the park from Star Lakes to White Chief Mountain. In the park, limited areal exposure of the unit occurs along the northern margin of the El Capitan pluton.	**Rise of the Batholith**—Rubidium-strontium isotopic age of about 108 million years.
		Aplite (Kap)	Bodies of aplite or fine-grained sugary alaskite containing tourmaline rosettes. Borders **Klh** in the park.	None Significant—Linear exposure of limited areal extent. Limited potential for geologic issues.	Linear, dike-like features. Exposed along the northeastern margin of the Lake Harriet pluton, Tower Peak quadrangle.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
	Fine Gold Intrusive Suite (Kfg)	Alaskite (Kal)	Light-colored, fine- to medium-grained leucogranite. Contains 1–2% small grains of biotite and red garnet.	None—This unit lies outside of the park boundaries.	**Granitic Bedrock**—Exposed in the southwestern corner of the Yosemite quadrangle, south of the park.	**Rise of the Batholith**—Granitic rocks in the Fine Gold Intrusive Suite that form part of the extensive Sierra Nevada Batholith.
		Granodiorite of Arch Rock (Kar)	Medium-grained, equigranular, hornblende-biotite granodiorite. Contains 6–8% mafic minerals, mostly subhedral biotite, but also subhedral hornblende and titanite. Contains potassium feldspar in poikilitic grains up to 1 cm (0.4 in) in size.	None Documented	**Granitic Bedrock**—Forms a small pluton in the Bass Lake Tonalite (**Kblt**) near the Arch Rock Entrance Station.	**Rise of the Batholith**—Similar in appearance to adjacent **Kblt**, but contains coarser, better-formed biotite grains. The two units may have similar cooling histories.
		Granodiorite of Crane Flat (Kcf)	Medium-grained biotite granodiorite. Contains evenly disseminated subhedral to anhedral biotite.	None Significant—Exposed on relatively gentle topography near the Crane Flat Ranger Station. Low potential for geologic issues.	**Granitic Bedrock**—Limited exposure near the western border of the park, Lake Eleanor quadrangle.	**Rise of the Batholith**—May have been emplaced at about the same time as the biotite granite of **Kar** in Yosemite Valley.
		Granodiorite of Sawmill Mountain (Ksm)	Medium to coarse grained, highly variable composition that ranges from biotite leucogranite to hornblende-biotite trondhjemite. Very similar in appearance to Kec.	None—This unit lies outside of the park boundaries.	**Granitic Bedrock**—Exposed just west of the park boundary in the Lake Eleanor quadrangle.	**Rise of the Batholith**—Uranium-lead isotopic age of 116.1 million years.
		Granite of Hogan Mountain (Khm)	Fine- to medium-grained leucocratic granite. Contains 2–4% small grains of opaque minerals and flakes of biotite.	None—Most of the unit is outside the park in the Bass Lake quadrangle. In the park, the unit has limited areal extent.	**Granitic Bedrock**—In the park, forms a small pluton centered on Mt. Savage in the southwestern corner of the park, Yosemite quadrangle.	**Rise of the Batholith**—Granitic rocks in the Fine Gold Intrusive Suite that form part of the extensive Sierra Nevada Batholith.
		Bass Lake Tonalite (Kblt)	Medium-grained, equigranular tonalite, granodiorite, and quartz diorite. Quartz is typically smaller and more irregularly shaped than in **Kec**. Generally foliated. Potassium feldspar is sparse. Abundant mafic inclusions of biotite, hornblende, and titanite.	**Rockfall**—Previous rockfalls have closed Highway 140 east of Yosemite View Lodge in El Portal.	**Granitic Bedrock**—Extends from the Bass Lake quadrangle, south of the park, into the western margin of the park.	**Rise of the Batholith**—Uranium-lead isotopic ages range from 124–105 million years. Previously called the Granodiorite of the Gateway.

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Age	Simplified Map Unit (Symbol) *Overview Sheet 1*	Map Unit (Symbol) *Colored if present on Overview Sheet 2*	Geologic Description	Geologic Issues	Geologic Features, Processes and General Location	Geologic History
CRETACEOUS (Lower)	Fine Gold Intrusive Suite (Kfg)	Tonalite of Oakhurst (Koh)	Light-colored, medium-grained hornblende-biotite tonalite, with faint planar foliation defined by orientation of mafic minerals. Indistinguishable in outcrop from **Kbm**.	None—These units lie outside of the park boundaries.	**Granitic Bedrock**—Exposed southwest of the park in the Mariposa quadrangle.	**Rise of the Batholith**—Uranium-lead isotopic age of about 105 million years.
		Tonalite of Blue Canyon (Kbm)	Light-colored, medium-grained granitic rocks, chiefly hornblende-biotite tonalite but grading locally into diorite, quartz diorite, granodiorite, and granite. Mostly equigranular. Potassium-feldspar phenocrysts up to 2 cm (0.8 in) long, biotite flakes up to 1 cm (0.4 in), and hornblende prisms up to 1.5 cm (0.6 in).		**Granitic Bedrock**—Exposed southwest of the park.	**Rise of the Batholith**—Considered to be part of **Kblt** by some geologists. Uranium-lead isotopic age of about 114 million years.
		Tonalite of Poopenaut Valley (Kpv)	Medium-grained biotite-hornblende tonalite. Ranges locally from granodiorite to quartz diorite, but generally has a uniform texture. Contains mafic minerals. Locally contains a porphyritic unit (**Kpvp**) with poikilitic potassium-feldspar phenocrysts up to 2 cm (0.8 in) long.	**Rockfall**—Rockfall potential on steep slopes adjacent to the Tuolumne River in Poopenaut Valley.	**Granitic Bedrock**—Exposed in the western part of the park in the Pinecrest and Lake Eleanor quadrangles.	**Rise of the Batholith**—May have been emplaced at about the same time as **Kbm**.
		Granodiorite of Hazel Green Ranch (Khg)	Medium-grained hornblende-biotite granodiorite and tonalite. Generally more felsic than Kpv but otherwise similar. Locally divided into mafic marginal facies (**Khgm**).	None—This unit lies outside of the park boundaries.	**Granitic Bedrock**—Adjacent to the western border of the park, Lake Eleanor quadrangle. Aligns with **Kblt** on the El Portal quadrangle to the south.	**Rise of the Batholith**—Granitic rocks in the Fine Gold Intrusive Suite that form part of the extensive Sierra Nevada Batholith.
	Lower Cretaceous Intrusive Rocks (Kia)	Granodiorite of Tueeulala Falls (Ktf)	Medium-grained hornblende-biotite granodiorite. Subhedral mafic minerals.	**Rockfall**—Rockfall potential on steeper slopes associated with Tueeulala Falls and Hetch Hetchy Reservoir. Infrastructure (dam buildings) is located west of **Ktf**.	**Granitic Bedrock**—Primarily exposed adjacent to the western end of Hetch Hetchy Reservoir, Lake Eleanor quadrangle.	**Rise of the Batholith**—Uranium-lead isotopic age of 108.7 million years.
		Granodiorite of Chowchilla Mountain (Kccm)	Medium-grained, biotite granodiorite. Contains about 8% fine, poorly formed mafic minerals, predominantly biotite but including less abundant hornblende.	None—These units lie outside of the park boundaries.	**Granitic Bedrock**—Forms a small igneous body in the southwestern part of the Yosemite quadrangle, west of the park.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
		Granodiorite of Iron Creek (Kirc)	Medium-grained, equigranular to porphyritic granodiorite and less abundant granite Contains up to 20% hornblende and biotite. May also contain abundant fine-grained potassium feldspar.		**Granitic Bedrock**—Exposed in the southeastern corner of the Yosemite quadrangle, southeast of the park.	**Rise of the Batholith**—Rubidium-strontium age of about 110 million years.
		Granodiorite of Wawona (Kww)	Light-colored, calcic granodiorite with 15% mafic minerals. Biotite is more abundant than hornblende. Contains coarser, more equant quartz in grains as large as 5 mm (0.2 in). Less mafic and less well-foliated than **Kblt**.	**Rockfall**—Limited areal extent. Potential rockfall from steeper slopes.	**Granitic Bedrock**—Forms a small pluton in the southwestern corner of the park, near Wawona in the Yosemite quadrangle.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
		Tonalite of South Wawona (Ksw)	Distinctive hornblende-biotite tonalite with 30–40% coarse euhedral phenocrysts of hornblende as long as 1 cm (0.4 in) and less abundant biotite in a very light-gray groundmass.	**Rockfall**—More limited areal extent than **Kww**. Exposed on gentler sloped than **Kww**.	**Granitic Bedrock**—Forms a band 300 m (1,000 ft) wide between **Kww** and **Kec** in the southwestern corner of the park, near Wawona in the Yosemite quadrangle.	
		Granite of Dorothy Lake (Kdl)	Light-pink, fine- to coarse-grained tourmaline-bearing granite. Contains rare miarolitic cavities. Locally intensely sheared, with tourmaline on shear surfaces.	**Rockfall**—Limited areal extent. Primarily exposed on gentle topography north of the park, but exposures on steeper slopes may present rockfall issues to the few visitors who might be in the area.	**Granitic Bedrock**—Exposed north of Dorothy Lake in the far northern part of the park, Tower Peak quadrangle. Most of the exposure lies outside of the park.	

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CRETACEOUS (Lower)	Lower Cretaceous Intrusive Rocks (Kia)	Granodiorite of Lake Harriet (Klh)	Dark-gray, moderately foliated granodiorite characterized by shreddy clots of biotite and hornblende. Aplite exposed along the northeastern margin.	**Rockfall**—Backcountry exposures primarily north of the park. Potential rockfall on steep slopes near Mary Lake.	**Granitic Bedrock**—Exposed in the far northern section of the park near Mary Lake and Craig Peak, Tower Peak quadrangle.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
		Leucogranite of Mount Clark (Kmc)	Very light gray, medium-grained, equigranular hornblende-biotite leucogranite.	**Rockfall**—Limited areal extent. Potential rockfall on steep slopes of Mount Clark.	**Granitic Bedrock**—Exposed on Mount Clark, Merced Peak quadrangle, southwestern part of the park.	
		Leucogranite (Klg)	Fine- to medium-grained equigranular biotite leucogranite.	None—These units lie outside of the park boundaries.	**Granitic Bedrock**—Forms isolated exposures southeast of the park in the Merced Peak quadrangle.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
		Quartz Diorite and Tonalite (Kqd)	Medium-gray to medium-light-gray, fine- to medium-grained equigranular quartz diorite and tonalite in small masses within granitic rocks and along contacts within metamorphic rocks.		Exposed south of the park in the Merced Peak quadrangle.	
		Quartz Diorite of Long Creek (Klc)	Light-gray, medium-grained quartz diorite containing equally abundant biotite and hornblende. Includes a zone of abundant inclusions.		Forms several small masses and dikes in metavolcanic rocks in Bench Canyon and in the drainage basin of Long Creek, south of the park in the Merced Peak quadrangle.	
CRETACEOUS or JURASSIC	Cretaceous/ Jurassic Intrusive Rocks (KJi)	Granodiorite of Camino Creek (KJcc)	Fine- to medium-grained unit with variable composition ranging from quartz diorite to quartz monzonite. Average composition of granodiorite. Mafic content is predominantly biotite. Commonly contains abundant inclusions of metamorphic rocks.	None—These units lie outside of the park boundaries.	**Granitic Bedrock**—Exposed south of the park in the Shuteye Peak quadrangle.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
		Quartz monzonite of Mono Lake (KJml)	The source map does not provide a detailed description.		Exposed east of the park and west of Mono Lakes, Mono Craters quadrangle.	
		Mafic intrusive rocks (KJma)	Medium- to coarse-grained hornblende gabbro, hornblendite, and pyroxenite.		One exposure of limited areal extent west of the park in the Lake Eleanor quadrangle.	
		Quartz diorite and older mafic plutonic rocks (KJqd)	Mafic plutonic rocks ranging greatly in composition, grain size, and texture. Probably includes rocks of different ages.	None Significant—Limited areal extent.	Limited exposures in the eastern part of the park, Tuolumne Meadows quadrangle.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
		Quartz diorite, diorite and gabbro (KJqdg)	Predominantly dark, medium grained, equigranular hornblende-biotite quartz diorite and less abundant diorite, gabbro, and tonalite in small scattered masses. Contains 20–40% mafic minerals. Fine-grained to coarsely porphyritic. Joints.	**Rockslides**—Joints in the Rockslides promote cliff collapse in Yosemite Valley.	**Diorite of the Rockslides**—The Rockslides contain the most closely-spaced joints in Yosemite Valley. Cliff collapse results in impressive talus piles.	**Rise of the Batholith**—The diorite enclaves in **Kec** may have originated from the magma that crystallized into the Diorite of the Rockslides.

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CRETACEOUS or JURASSIC	Cretaceous/ Jurassic Intrusive Rocks (KJi)	Diorite (Jd)	Diorite with extremely variable grain size, texture, and composition.	None Significant—Isolated outcrops of limited areal extent in the backcountry.	Occurs as generally small, irregularly shaped bodies throughout the Tower Peak quadrangle.	**Rise of the Batholith**—Some bodies are older and some younger than the plutonic rocks with which they are in contact.
CRETACEOUS or JURASSIC	Cretaceous/ Jurassic Intrusive Rocks (KJi)	Hornblende gabbro (Kgb)	Two bodies of hornblende gabbro exposed near the center of the Tower Peak quadrangle.	None Significant—Isolated outcrops of limited areal extent in the backcountry.	Two igneous bodies have intruded a metasedimentary sequence and, in turn, have also been metamorphosed.	**Rise of the Batholith**—Uranium-lead zircon age of about 148 million years.
CRETACEOUS or JURASSIC	Cretaceous/ Jurassic Intrusive Rocks (KJi)	Diabase of Reversed Creek (Jdrc)	Diabase. The source map does not provide a detailed description.	None—These units lie outside of the park boundaries.	Exposed north of Reversed Creek and west of June Lake in the Mono Craters quadrangle, east of the park.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
CRETACEOUS or JURASSIC	Cretaceous/ Jurassic Intrusive Rocks (KJi)	Diorite of Waugh Lake (Jwl)	Diorite. The source map does not provide a detailed description.	None—These units lie outside of the park boundaries.	**Granitic Bedrock**—Exposed east of the park in the Mono Craters quadrangle.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
CRETACEOUS or JURASSIC	Cretaceous/ Jurassic Intrusive Rocks (KJi)	Diorite of Bloody Canyon (Jdbc)	Diorite. The source map does not provide a detailed description.	None—These units lie outside of the park boundaries.	**Granitic Bedrock**—Small exposure west of Walker Lake in Bloody Canyon, Mono Craters quadrangle, east of the park.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
CRETACEOUS or JURASSIC	Cretaceous/ Jurassic Intrusive Rocks (KJi)	Felsic dikes and masses (KJfd)	Fine-grained, rhyolitic felsic dikes and igneous masses. Commonly exhibits flow banding.	None—These units lie outside of the park boundaries.	Most dikes occur as a swarm in and near the granodiorite near King Creek (**KJf**), Devils Postpile quadrangle.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
CRETACEOUS or JURASSIC	Cretaceous/ Jurassic Intrusive Rocks (KJi)	Mafic dikes and masses (KJmd)	Fine- to medium-grained dikes and igneous masses, occasionally porphyritic or amygdaloidal.	None—These units lie outside of the park boundaries.	Exposed east of the park in the Devils Postpile quadrangle.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
CRETACEOUS or JURASSIC	Cretaceous/ Jurassic Intrusive Rocks (KJi)	Granodiorite of King and Fish Creeks (KJf)	Fine- to coarse-grained granodiorite. Contain numerous metavolcanic inclusions. Intruded by **Kcp** and **Kmg**. King Creek masses are cut by numerous mafic and rhyolitic dikes.	None—These units lie outside of the park boundaries.	**Granitic Bedrock**—Mapped in the Devils Postpile quadrangle, east of the park.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
CRETACEOUS or JURASSIC	Cretaceous/ Jurassic Intrusive Rocks (KJi)	Fine-grained quartz monzonite (KJfg)	Fine-grained aplitic quartz monzonite.	None—These units lie outside of the park boundaries.	Exposed as a small mass and associated dikes at the north edge of the Shuteye Peak quadrangle, southeast of the park.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
CRETACEOUS or JURASSIC	Cretaceous/ Jurassic Intrusive Rocks (KJi)	Dark granodiorite and other mafic plutonic rocks (KJd)	Dark, medium-grained hornblende-biotite granodiorite, quartz diorite, diorite, and gabbro.	None—These units lie outside of the park boundaries.	**Granitic Bedrock**—Exposed southeast of the park in the Shuteye Peak quadrangle.	**Rise of the Batholith**—Various small bodies of mafic intrusive rock of uncertain ages relative to most other intrusive rocks.

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JURASSIC	Jurassic Intrusive Rocks (Ji)	Quartz diorite of South Fork of Tuolumne River (Jqtr)	Dark-gray, coarse-grained, foliated biotite-hornblende quartz diorite.	None Significant—Limited areal extent.	Exposed in the southwestern corner of the Hetch Hetchy Reservoir quadrangle.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
		Diorite (Jdio)	Fine-grained, massive, well-jointed, dark greenish-gray diorite composed of hornblende, biotite, oligoclase, augite, and quartz.	None—This unit lies outside of the park boundaries.	Exposed north of the park in the Matterhorn Peak quadrangle.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
		Quartz porphyry (Jp)	Light-gray, dense, weakly lineated, and foliated quartz porphyry with phenocrysts of clear quartz and dull-white oligoclase.	**Rockfall**—Linear exposure in the backcountry. Minor potential for rockfall.	Thin, northwest-trending exposure south of Virginia Peak, northeastern border of the park, Matterhorn Peak quadrangle.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
		Serpentinite (Jsp)	Dark, mottled green and brown, highly sheared serpentinite. Contains chrysotile, magnetite, and anthophyllite.	None—These units lie outside of the park boundaries.	Exposed north of the park in the Matterhorn Peak quadrangle.	**Rise of the Batholith**—Derived in part from pyroxenite and andesitic lavas.
		Granite gneiss (Jgn)	Light- to dark- gray, massive, well-jointed granite gneiss. Clear quartz porphyroblasts in a matrix of quartz, potash feldspar, plagioclase, and biotite.			**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
		Granite of Cottonwood Creek (Jcc)	Chiefly biotite granodiorite, locally porphyritic with potassium feldspar phenocrysts.		**Granitic Bedrock**—Exposed west of the park in the Pinecrest quadrangle but continues into the Lake Eleanor quadrangle as **Jwr**.	**Rise of the Batholith**—Uranium-lead isotopic ages of 148 million years and 151 million years (Late Jurassic).
		Granite of Woods Ridge (Jwr)	Fine- to medium-grained porphyritic biotite granite and granodiorite. Characteristically contains coarse-grained phenocrysts of potassium feldspar and biotite flakes.		**Granitic Bedrock**—Exposed west of the park in the Lake Eleanor quadrangle but continues into the Pinecrest quadrangle as **Jcc**.	**Rise of the Batholith**—Uranium-lead isotopic age of 150.9 million years (Late Jurassic).
		Tonalite of Granite Creek (Jgc, Jgcm)	Medium grained hornblende-biotite tonalite and granodiorite. Commonly strongly foliated. **Jgcm**: mafic marginal unit of medium-grained hornblende-biotite gabbro.		**Granitic Bedrock**—Exposed just west of the park in the Lake Eleanor quadrangle.	**Rise of the Batholith**—Uranium-lead isotopic ages of 165.7 million years and 162.6 million years (Middle Jurassic).
		Diorite (Jdi)	Dark-gray to black, fine-grained diorite. Contains biotite and hornblende in variable proportions.	None Significant—Isolated exposures of limited areal extent.	Exposed in the Hetch Hetchy Reservoir quadrangle.	**Rise of the Batholith**—Occurs as inclusions in granitic rocks of Jurassic age and may be mostly chemically reconstituted metamorphic rocks.
		Quartz monzonite of Billy Lake (Jbl)	The source map does not provide a detailed description.	None—These units lie outside of the park boundaries.	Exposed east of the park in the Mono Craters quadrangle.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.

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JURASSIC	Jurassic Intrusive Rocks (Ji)	Granodiorite of Rush Creek (Jrc)	Medium-grained, ranging in composition from granodiorite to diorite. Generally exhibits a pronounced linear structure and less pronounced foliation.	None—These units lie outside of the park boundaries.	**Granitic Bedrock**—Exposed east of the park in the Mono Craters and Devils Postpile quadrangles.	**Rise of the Batholith**—Granitic rocks that form part of the extensive Sierra Nevada Batholith.
TRIASSIC	Triassic Intrusive Rocks (TRi)	Garnet bearing aplite (TRlvg)	Aplite containing garnet. The source map does not provide a detailed description.	None—These units lie outside of the park boundaries.	Exposed east of the park in the Mono Craters quadrangle.	
	Scheelite Intrusive Suite (TRs)	Granite of Lee Vining Canyon (TRlv)	Medium-grained granite with varied texture and appreciable dense, fine-grained felsic rock, commonly porphyritic, locally banded. Numerous dikes and sills.	None—These units lie outside of the park boundaries.	**Granitic Bedrock**—Exposed east of the park in Mono Craters and Devils Postpile quadrangles.	**Rise of the Batholith**—Possibly younger than Triassic. A Rubidium-strontium whole-rock analysis indicates an age of about 190 million years (Early Jurassic).
		Wheeler Crest Granodiorite (TRwc)	Medium-grained, commonly porphyritic granodiorite with phenocrysts of potassium-feldspar. Biotite and hornblende are the chief mafic minerals.			**Rise of the Batholith**—Possibly younger than Triassic. Potassium-argon isotopic analysis of samples from the Mount Tom quadrangle to the southeast yielded ages of about 100 million years (Early Cretaceous).

Metamorphic Rock Units: Western Metamorphic Belt

Age	Simplified Map Unit (Symbol)	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features, Processes and General Location	Geologic History
JURASSIC	Western Metamorphic Belt, Jurassic Rocks (Jwmb)	Greenstone of Bullion Mountain (Jbu)	Chiefly andesitic and basaltic metatuff and metatuff breccia, but includes lava flows.	None—These units lie outside of the park boundaries.	**Western Metamorphic Belt**—Exposed west of the park in the El Portal quadrangle.	**Rise of the Batholith**—Volcanic origins.
		Mafic volcanic rocks (Jmav)	Chiefly amphibolites.		**Western Metamorphic Belt**—Exposed in the Bass Lake quadrangle, south of the park.	**Rise of the Batholith**—May have been derived from basaltic and andesitic metatuff, metatuff breccia, and flows.
JURASSIC or TRIASSIC	Western Metamorphic Belt, Pre-Cretaceous Rocks (pKwmb)	Metavolcanic rocks east of Melones Fault (pKmv)	Chlorite-muscovite schist, hornfels, and amphibolite. Equivalents of basalt and andesite in lava flows, tuff beds, volcanic breccias, and small intrusive bodies. Mafic phenocrysts.	None—These units lie outside of the park boundaries.	**Western Metamorphic Belt**—Locally interbedded with metasedimentary rocks or intruded by small bodies of ultramafic rocks. Exposed in the Mariposa quadrangle, south of the park.	**Rise of the Batholith**—A Jurassic ammonite has been reported in rocks continuous with **pKmv** to the northwest. Elsewhere, **pKmv** are older than the Cretaceous granitic rocks that intrude them.
		Metasedimentary rocks east of Melones Fault (pKsmf)	Slate, phyllite, mica schist, hornfels, quartzite, and metaconglomerate. Equivalents of clastic sedimentary rocks except near intrusive contacts where original rocks have been altered to hornfels and/or coarse mica schist.		**Western Metamorphic Belt**—Bedding is at high angles locally but generally not discernible in fine-grained rocks. Gradational bedding prominent in a few places. Exposed south of the park in the Mariposa quadrangle.	**Rise of the Batholith**—Age is uncertain. The unit is at least as old as Jurassic, and part or all may be Paleozoic. Outcrops are continuous with rocks assigned to the Calaveras Complex (Upper Permian–Lower Jurassic) in adjoining quadrangles.
TRIASSIC	Western Metamorphic Belt, Triassic Rocks (TRwmb)	Slate and phyllite (TRsp)	Slate, phyllite, quartzite and probably some chert.	None—These units lie outside of the park boundaries.	**Western Metamorphic Belt**—Forms the outer parts of the Coarsegold roof pendant, adjacent to **Jmav** in the Bass Lake quadrangle, south of the park.	**Rise of the Batholith**—Metamorphosed sedimentary rocks.
		Phyllite of Briceburg (TRpb)	Chiefly phyllite, but includes quartzite, chert, graywacke, and limestone olistoliths (**TRpbls**).		**Western Metamorphic Belt**—Conodonts. Exposed west of the park in the El Portal quadrangle.	**Rise of the Batholith**—The limestone olistoliths contain Early Triassic conodonts (small fossils important for age-dating).

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TRIASSIC	Western Metamorphic Belt, Triassic Rocks (TRwmb)	Phyllite and chert of Hite Cove (TRh)	Sequences of rhythmically banded chert in a matrix of phyllite. A few limestone lenses (**TRhls**) are present, some of which may be olistoliths. Locally contains metabasalt (**TRhmba**).	None—These units lie outside of the park boundaries.	**Western Metamorphic Belt**—Forms an extensive northwest-trending outcrop west of the park in the Lake Eleanor and El Portal quadrangles.	**Rise of the Batholith**—An interstratified bed in the central part of this unit has yielded fossil conodonts indicating an Early Triassic age.
PALEOZOIC ERA	Western Metamorphic Belt, Paleozoic Rocks (PZwmb)	Quartzite and phyllite (PZqs)	Characterized by massive quartzite beds.	None—These units lie outside of the park boundaries.	**Western Metamorphic Belt**—Exposed in the Bass Lake quadrangle.	**Assembling California**—Primarily metamorphosed sandstone.
		Paleozoic rocks of the Western Metamorphic Belt of Huber and others (1989) (PZmsq, PZmr, PZmdd, PZpr, cmp)	**PZmsq**: quartz-mica schist and quartzite.	None Significant—Exposures have a limited areal extent in the backcountry and pose little potential for significant geologic issues.	**Western Metamorphic Belt**—Minor exposures of limited areal extent in the Hetch Hetchy Reservoir quadrangle. **PZmr** is near Mount Hoffman, and **PZmdd** is located on the slope of Coyote Rocks. **May Lake Quartzite**—**PZmsq** mapped southwest of May Lake.	**Assembling California**—Metamorphosed sandstone and siltstone; associated with the May Lake conundrum involving beach sand deposited far away from the shoreline (see report fig. 20) 500-600 million years ago. The emplacement of Sierra Nevada batholith (and possible faulting) metamorphosed and deformed the rocks.
			PZmr: marble.			**Assembling California**—Metamorphosed limestone.
			PZmdd: metamorphosed dacites and rhyodacites.			**Assembling California**—Metamorphosed volcanic rocks.
			PZpr: massive quartzite interbedded with phyllite and schist on Pilot Ridge. Siliceous marble and skarn occur locally.	**Rockslides**—Exposed primarily outside of the park, but potential rockslides may impact the Mariposa and Tuolumne groves.	**Western Metamorphic Belt**—Exposed along the western border of the park in the El Portal and Lake Eleanor quadrangles.	**Assembling California**—Metamorphosed sedimentary rocks including sandstone, siltstone, and limestone.
			cmp: carbonaceous, metamorphosed mudstone (pelite).	None—This unit lies outside of the park boundaries.	**Western Metamorphic Belt**—Northwest-trending exposure west of the park in the El Portal quadrangle.	**Assembling California**—The unit may be tectonic, rather than stratigraphic, in origin and associated with the Calaveras-Shoo Fly thrust.

Metamorphic Rock Units: Eastern Metamorphic Belt

Age	Simplified Map Unit (Symbol)	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features, Processes and General Location	Geologic History
CRETACEOUS	Eastern Metamorphic Belt, Cretaceous Rocks (Kemb)	Metaandesite and metarhyodacite (Km)	Gray, slightly metamorphosed flows and tuff. Metaandesite contains euhedral tabular phenocrysts of plagioclase up to 5 mm (0.2 in) long.	None—This unit lies outside of the park boundaries.	**Eastern Metamorphic Belt**—Forms small outcrops on the flanks of Raymond Mountain, Yosemite quadrangle.	**Rise of the Batholith**—Metamorphosed volcanic rocks.
		Metavolcanic rocks – tuff and flows (Kmv)	Predominantly gray metarhyodacite tuff containing flattened dark lapilli and altered phenocrysts of plagioclase, quartz, and altered hornblende in a fine-grained groundmass.	None Significant—Isolated outcrops of limited areal extent.	**Eastern Metamorphic Belt**—Exposed southeast of Mariposa Grove and in small masses elsewhere in the Yosemite quadrangle.	**Rise of the Batholith**—Metamorphosed volcanic rocks.

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Age	Simplified Map Unit (Symbol) *Overview Sheet 1*	Map Unit (Symbol) *Colored if present on Overview Sheet 2*	Geologic Description	Geologic Issues	Geologic Features, Processes and General Location	Geologic History
CRETACEOUS	Eastern Metamorphic Belt, Cretaceous Rocks (Kemb)	Metavolcanic rocks, undifferentiated (Kmva)	Predominantly medium- to light-gray, quartzofeldspathic (quartz- and feldspar-rich) hornfels, epidote-amphibolite hornfels, and less abundant schist and gneiss. Includes dark-gray flows of porphyritic metabasalt and meta-andesite and well-bedded volcanogenic siltstone, sandstone, and conglomerate along the southeastern edge of the park.	None Significant—Isolated outcrops of limited areal extent.	**Eastern Metamorphic Belt**—Massive to weakly foliated rocks having well-preserved relict textures derived from massive rhyodacitic vitric and vitric-crystal tuff, lapil1i tuff, and tuff breccia. Exposed along the southeastern border of the park near Merced and Sing peaks, Merced Peak quadrangle.	**Rise of the Batholith**—Metamorphosed pyroclastic rocks, lava flows, and other volcanic rocks originally ranging in composition from basalt to rhyolite.
		Quartzo-feldspathic gneiss (Kmq)	Very light-gray, fine-grained, weakly foliated rocks.	None—This unit lies outside of the park boundaries.	**Eastern Metamorphic Belt**—Exposed near Jackass Meadow, Merced Peak quadrangle.	**Rise of the Batholith**—Derived from silicic tuff or volcanic intrusive rocks of granitic composition.
		Metarhyolite (Kmr)	Light-gray quartzofeldspathic hornfels.	None Significant—Isolated outcrop of limited areal extent.	**Eastern Metamorphic Belt**—Forms a 20-m (66-ft)-thick layer near Cold Springs Meadow, Merced Peak quadrangle.	**Rise of the Batholith**—Derived from crystal-vitric tuff, breccia, and flow rock of rhyolitic composition.
		Metadacite porphyry (Kdp)	Fine-grained gray rock composed of plagioclase phenocrysts in a matrix of plagioclase, quartz, and opaque minerals.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—These units are exposed between Tioga Lake and the eastern boundary of the park, Tuolumne Meadows quadrangle. All have limited areal extent. **Kph** contains larger plagioclase grains and cross-beds in some places.	**Rise of the Batholith**—Metamorphosed plutonic rock.
		Felsic metatuff (Kft)	Quartz and feldspar crystals abundant, and collapsed pumice fragments present locally. Includes thinly laminated calc-silicate rock composed of quartz, feldspar, epidote, and opaque minerals.			**Rise of the Batholith**—Metamorphosed volcanic rock.
		Pelitic hornfels (Kph)	Thin-bedded fine-grained metasiltstone composed of tiny grains of plagioclase, muscovite, quartz, and opaque minerals.			**Rise of the Batholith**—Metamorphosed siltstone.
		Interstratified mafic and felsic tuffs (Kmft)	Includes a lens of pebble conglomerate. Tuffs are composed chiefly of quartz, biotite, plagioclase, and opaque minerals.			**Rise of the Batholith**—Metamorphosed volcanic rock, primarily tuff.
CRETACEOUS or JURASSIC	Eastern Metamorphic Belt, Cretaceous/Jurassic Rocks (KJemb)	Mafic metatuff and metatuff breccia (KJm)	Medium- to dark-gray metamorphosed pyroclastic rocks. Rock is typically a quartz-feldspar-mica hornfels with amphibole locally abundant. Does not contain fragments of nonvolcanic rock. Ranges from fine-grained massive metatuff to metatuff breccia with lithic fragments up to 0.5 m (1.6 ft) long.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Exposed south of the park.	
		Metarhyolite tuff (KJr)	Light-gray metatuff. Includes metatuff breccia and flow-banded rhyolite.		**Eastern Metamorphic Belt**—Forms a dark, slightly metamorphosed, rhyodacite porphyry dike about 9 m (30 ft) wide near Star Lakes, south of the park.	
JURASSIC	Eastern Metamorphic Belt, Jurassic Rocks (Jemb)	Metavolcanic rocks south of Ireland Lake (Jvil)	Predominantly tuff-breccia of intermediate composition containing angular to rounded fragments that average 2–10 cm (0.8–4 in) wide but are as large as 75 cm (30 in).	**Rockfall**—Isolated backcountry exposures of limited areal extent near Ireland Lake. Rockfall potential on steeper slopes, but no significant geologic issues for the park.	**Eastern Metamorphic Belt**—Exposed in the Tuolumne Meadows quadrangle, south of Ireland Lake and includes limited exposures northwest of Hooper Peak and west of Babcock Lake.	**Rise of the Batholith**—Metamorphosed volcanic rocks.

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JURASSIC	Eastern Metamorphic Belt, Jurassic Rocks (Jemb)	Metavolcanic rocks west of Ireland Lake (Jsil)	Thinly laminated calc-silicate hornfels and quartz-biotite schist with epidote layers and eye-like structures. Locally interbedded with volcanic conglomerate.	**Rockfall**—Isolated backcountry exposures of limited areal extent near Ireland Lake. Rockfall potential on steeper slopes, but no significant geologic issues for the park.	**Eastern Metamorphic Belt**—Exposed west of Ireland Lake in the Tuolumne Meadows quadrangle.	**Rise of the Batholith**—Metamorphosed volcanic rocks
		Saddlebag Lake area rocks (Jlb, Jrt)	**Jlb**: tuffaceous lake beds. Thinly bedded and fine grained volcanogenic sediment. Common minerals include plagioclase, quartz, biotite, and hornblende.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Exposed in the Saddlebag Lake area, east of the park in the Tuolumne Meadows quadrangle.	**Rise of the Batholith**—Metamorphosed volcanic rocks. **Jrt**: Rubidium-strontium whole-rock age of about 185 million years (Early Jurassic).
			Jrt: rhyolite ash-flow. Light-gray tuff with a few flattened pumice fragments. Phenocrysts of quartz and plagioclase.			
		Undifferentiated metasedimentary rocks (Jm)	Predominantly medium-gray, fine-grained, thinly bedded micaceous metaquartzite, but includes less abundant gray quartz-biotite hornfels and schist, red-weathering quartz-plagioclase hornfels, tactite, and marble.	None—Exposures in the park have limited areal extent and pose no geologic issue for the park.	**Eastern Metamorphic Belt**—Exposed along the southern border of the park in the Merced Peak quadrangle. Most of the mapped exposure lies south of the park.	**Rise of the Batholith**—Metamorphosed sedimentary rocks.
		Tactite (Jmt)	Mostly epidote-pyroxene-garnet-magnetite rock.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Limited exposures south of the park in the Merced Peak quadrangle.	**Rise of the Batholith**—Metamorphosed sedimentary rocks, including limestone and conglomerate.
		Quartz-pebble conglomerate (Jmq)	Quartz-pebble conglomerate. The source map does not provide a detailed description.		**Eastern Metamorphic Belt**—Exposures are near Cold Springs Meadow, Merced Peak quadrangle, south of the park.	
		Marble (Jmm)	Medium-gray cherty marble.		**Eastern Metamorphic Belt**—Exposed east of Chiquito Lake and west of Gray Peak, Merced Peak quadrangle, just south of the park.	
		Undifferentiated metasedimentary and metavolcanic rocks north of Hooper Peak (Jmsv)	Metasedimentary and metavolcanic rocks. Includes abundant dikes of the adjacent plutonic rocks.	None Significant—Limited areal extent in the backcountry.	**Eastern Metamorphic Belt**—Exposed in the northwest corner of the Tuolumne Meadows quadrangle.	**Rise of the Batholith**—Metamorphosed sedimentary and volcanic rocks.
		Ritter Range roof pendant rocks (Jxt, Jsm, Jth)	**Jxt**: graywackes, volcanic tuffs and flows, sandstones.	None Significant—Limited areal extent.	**Eastern Metamorphic Belt**—Exposures of limited areal extent between Mount Dana and Gaylor Peak, eastern border of the park, Mono Craters quadrangle.	**Rise of the Batholith**—Metamorphosed sedimentary and volcanic rocks.
			Jsm: marble and calc-silicate hornfels.			**Rise of the Batholith**—Metamorphosed limestone and siltstone.

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JURASSIC	Eastern Metamorphic Belt, Jurassic Rocks (Jemb)	Ritter Range roof pendant rocks (Jxt, Jsm, Jth)	**Jth**: volcanic tuffs and flows, shale and hornfels	None Significant—Limited areal extent.	**Eastern Metamorphic Belt**—Exposures of limited areal extent between Mount Dana and Gaylor Peak, eastern border of the park, Mono Craters quadrangle.	**Rise of the Batholith**—Metamorphosed sedimentary and volcanic rocks.
		Ritter Range rocks (Jbr, Jts, Jdf, Jeg, Jab)	**Jbr**: undifferentiated metavolcanics, chiefly breccia. Highly varied unit, but consists chiefly of tuff breccia, somewhat lesser amounts of crystal tuff and crystal-lithic tuff, and much smaller flows, hypabyssal intrusives, and bedded tuff. Composition ranges from rhyolite to basalt but averages near dacite or rhyodacite. Lithic fragments may reach 0.3 m (1 ft) in maximum dimension. Fragments are typically volcanic but may be sedimentary or granitoid.	**Rockfall**—Limited areal extent. Steep slopes carry the potential for rockfall, but limited exposures would result in minor geologic impact.	**Eastern Metamorphic Belt**—An area of extensive migmatization occurs south of Bench Canyon, east of the park. Exposure extends into the park from the Devils Postpile quadrangle.	**Rise of the Batholith**—Total thickness of Ritter Range metavolcanic rocks is approximately 4,600 m (15,000 ft).
			Jts: tuffaceous metasandstone and metasiltstone.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Thin slivers of metamorphic rock associated with **Jbr**. Exposed east of the park in the Devils Postpile quadrangle. **Jts**: exposed south of Bench Canyon. **Jdf**: exposed north of Twin Island Lakes.	**Rise of the Batholith**—Volcanic flows and metamorphosed sandstone and siltstone. **Jeg**: interpreted as metamorphosed limestone.
			Jdf: metadacite flow. Medium dark-gray to dark-gray thin dacite flow or hypabyssal intrusive in structureless pyroclastic rocks.			
			Jeg: narrow belt of epidote-garnet rock.			
			Jab: meta-andesite and metabasalt. Gray, fine-grained to porphyritic, thin to thick flows with some tuffaceous rocks. Contains tabular plagioclase (oligoclase to labradorite) phenocrysts up to 3 cm (1.2 in) in maximum dimension.			
		Twin Island Lakes rocks (Jtlb, Jma, Jtis)	**Jtlb**: basalt. Thick flows of medium dark-gray to dark-gray basalt. Massive and porphyritic.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Exposed west of Twin Island Lakes, east of the park in the Devils Postpile quadrangle.	**Rise of the Batholith**—Metamorphic rocks near Twin Island Lakes are approximately 3,000 m (10,000 ft) thick.
			Jma: dark-gray sequence of thin to thick andesite and basalt flows, commonly interlayered with thin layers of tuffaceous rocks. Tabular plagioclase phenocrysts, local quartz amygdules.			
			Jtis: a generally well-bedded sequence of chiefly siltstone and fine-grained sandstone, tuffaceous in part. Includes tremolite-bearing carbonaceous marble, carbonaceous hornfels and slate, and conglomerate.			
		Virginia Lakes sequence rocks (Jrs, Jmb, Jas, Jrtp, Jqhm, Jhm, Jqhg)	**Jrs**: quartz-sericite schist and phyllonite. Highly sheared.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Thin slivers of metamorphic rocks north of the park in the Matterhorn Peak quadrangle.	**Rise of the Batholith**—Derived principally from lavas of rhyolitic composition.

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JURASSIC	Eastern Metamorphic Belt, Jurassic Rocks (Jemb)	Virginia Lakes sequence rocks (Jrs, Jmb, Jas, Jrtp, Jqhm, Jhm, Jqhg)	**Jmb**: metabasalt. Dark-gray to dark greenish - brown, dense, fine-grained, well-jointed.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Thin slivers of metamorphic rocks north of the park in the Matterhorn Peak quadrangle.	**Rise of the Batholith**—Metamorphosed basalt.
JURASSIC	Eastern Metamorphic Belt, Jurassic Rocks (Jemb)	Virginia Lakes sequence rocks (Jrs, Jmb, Jas, Jrtp, Jqhm, Jhm, Jqhg)	**Jas**: amphibolite and biotite-hornblende schist. Dark- to light-green, gray, and purplish andesitic and dacitic lavas and pyroclastic deposits; metamorphosed into amphibolites and biotite-hornblende schist.	None Significant—Backcountry exposures with limited areal extent in the park. Rockfall potential on some of the steeper slopes.	**Eastern Metamorphic Belt**—Tuff is locally sheared to slate. Northwest-trending exposures along the northeastern border of the park, Matterhorn Peak quadrangle.	**Rise of the Batholith**—The Virginia Lakes sequence is approximately 300 m (1,000 ft) thick and consists predominantly of metamorphosed lava flows and interlayered pyroclastic deposits. The units are highly interfingered and stratigraphically repeated, thus this stratigraphic order is only a crude representation.
JURASSIC	Eastern Metamorphic Belt, Jurassic Rocks (Jemb)	Virginia Lakes sequence rocks (Jrs, Jmb, Jas, Jrtp, Jqhm, Jhm, Jqhg)	**Jrtp**: creamy-white to light-gray, locally stained brown by limonite, fine-grained, highly sheared, tuffs and tuff breccias of rhyolitic and dacitic composition metamorphosed into quartz-sericite schist and phyllonite.	None Significant—Backcountry exposures with limited areal extent in the park. Rockfall potential on some of the steeper slopes.	**Eastern Metamorphic Belt**—Tuff is locally sheared to slate. Northwest-trending exposures along the northeastern border of the park, Matterhorn Peak quadrangle.	**Rise of the Batholith**—The Virginia Lakes sequence is approximately 300 m (1,000 ft) thick and consists predominantly of metamorphosed lava flows and interlayered pyroclastic deposits. The units are highly interfingered and stratigraphically repeated, thus this stratigraphic order is only a crude representation.
JURASSIC	Eastern Metamorphic Belt, Jurassic Rocks (Jemb)	Virginia Lakes sequence rocks (Jrs, Jmb, Jas, Jrtp, Jqhm, Jhm, Jqhg)	**Jqhm**: dark-gray to dark-brown, well-bedded, banded quartzofeldspathic hornfels, andalusite-bearing; calc-silicate hornfels, metaconglomerate (**Jqhmc**) and thin, gray marble beds.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Exposed northeast of the park in the Matterhorn Peak quadrangle.	**Rise of the Batholith**—Part of the Virginia Lakes sequence.
JURASSIC	Eastern Metamorphic Belt, Jurassic Rocks (Jemb)	Virginia Lakes sequence rocks (Jrs, Jmb, Jas, Jrtp, Jqhm, Jhm, Jqhg)	**Jhm**: streaked light-gray and white, medium- to fine-grained, poorly layered massive marble. Locally contains white wollastonite and pale orange-brown garnet.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Exposed northeast of the park in the Matterhorn Peak quadrangle.	**Rise of the Batholith**—Part of the Virginia Lakes sequence.
JURASSIC	Eastern Metamorphic Belt, Jurassic Rocks (Jemb)	Virginia Lakes sequence rocks (Jrs, Jmb, Jas, Jrtp, Jqhm, Jhm, Jqhg)	**Jqhg**: light-gray, brown to dark-gray, bedded, banded siltstone, sandstone, chert, and minor conglomerate; all metamorphosed to quartzofeldspathic hornfels, calc-silicate hornfels, quartzite, metachert, and metaconglomerate.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Exposed northeast of the park in the Matterhorn Peak quadrangle.	**Rise of the Batholith**—Part of the Virginia Lakes sequence.
JURASSIC, TRIASSIC, or OLDER	Eastern Metamorphic Belt, Pre-Cretaceous Rocks (pKemb)	Basaltic metavolcanic rocks (pKmvb)	Basaltic and andesitic metavolcanic rocks derived from lava flows and tuffs. Includes associated dark metasedimentary rocks.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Exposed in the Tower Peak quadrangle, north of the park.	**Rise of the Batholith**—Derived from lava flows and tuffs.
JURASSIC, TRIASSIC, or OLDER	Eastern Metamorphic Belt, Pre-Cretaceous Rocks (pKemb)	Rhyolitic metavolcanic rocks (pKmvr)	Rhyolitic and dacitic metavolcanic rocks derived from tuffs, some probably ignimbrites. Includes metarhyolite breccia.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Associated with **pKmvb**, north of the park in the Tower Peak quadrangle.	**Rise of the Batholith**—Derived from volcanic tuffs.
JURASSIC, TRIASSIC, or OLDER	Eastern Metamorphic Belt, Pre-Cretaceous Rocks (pKemb)	Quartz-biotite-plagioclase schist (pKs)	Fine- to medium-grained layered schist of probable metasedimentary origin.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Exposed north of the park in the Pinecrest quadrangle.	**Rise of the Batholith**—Protoliths for this unit are probably pre-Cretaceous in age.
JURASSIC, TRIASSIC, or OLDER	Eastern Metamorphic Belt, Pre-Cretaceous Rocks (pKemb)	Metasedimentary rocks (pKms)	Includes quartzite, marble, biotite-andalusite schist, meta-conglomerate, and calc-silicate hornfels. Predominate rock type indicated in local areas: **pKmsq**, white, cross-bedded quartzite; **pKmsm**, white to gray marble; **pKmsh**, fine-grained hornfels.	None—Backcountry exposures are predominately north of the park and pose no geologic issues for the park.	**Eastern Metamorphic Belt**—Exposed along the park boundary near Bigelow Peak, Tower Peak quadrangle. Most exposures are north of the park.	**Rise of the Batholith**—The original sandstone, limestone, and siltstone were metamorphosed to quartzite, marble, and hornfels, respectively.

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<tr><td rowspan="2">JURASSIC, TRIASSIC, or OLDER</td><td rowspan="10">Eastern Metamorphic Belt, Pre-Cretaceous Rocks (pKemb)</td><td>Schist and metaquartzite, tactite (pKsq, pKt)</td><td>pKsq: dark biotite schist, gray metaquartzite, and less abundant rusty-weathering argillite. Mapped as equivalent to PZqs in the Bass Lake quadrangle to the south. pKt: tactite layer, composed mostly of epidote, pyroxene, garnet, and magnetite.</td><td>None—These units lie outside of the park boundaries.</td><td>Eastern Metamorphic Belt—Metasedimentary rocks exposed near the southeastern corner of the Yosemite quadrangle.</td><td>Rise of the Batholith—Metamorphosed sandstone and siltstone.</td></tr>
<tr><td>Calc-silicate hornfels, quartzite and schist (pKcs)</td><td>Hornfels, quartzite, and schist. The source map does not provide a detailed description.</td><td>None—Unit is in a narrow, northeast-trending depression that was carved by glaciers. No known geologic hazards are associated with these units.</td><td>May Lake Quartzite—In isolated outcrops between Glen Aulin and May Lake, Tuolumne Meadows quadrangle.</td><td rowspan="2">Rise of the Batholith—Units are associated with the May Lake conundrum involving beach sand deposited far away from the shoreline (see report fig. 20) 500-600 million years ago. Emplacement of the Sierra Nevada batholith metamorphosed and deformed the rocks.</td></tr>
<tr><td rowspan="8">JURASSIC or TRIASSIC</td><td>Massive quartzite (pKq)</td><td>Highly jointed metamorphic quartzite.</td><td>None—Associated with pKcs.</td><td>May Lake Quartzite—Forms a northeast–southwest trending layer of quartzite in the depression filled by May Lake at the base of Mount Hoffman.</td></tr>
<tr><td rowspan="7">Shadow Creek and Mammoth Crest rocks (JTRu, JTRpz, JTRqa, JTRa, JTRx, JTRd, JTRc, JTRss)</td><td>JTRu: undifferentiated metavolcanic rocks. Highly varied unit that includes (in order of decreasing abundance): crystal-lithic tuff, tuff breccia, tuffaceous sandstone and siltstone, flows and hypabyssal intrusives, mostly mafic.</td><td rowspan="7">None—These units lie outside of the park boundaries.</td><td rowspan="7">Eastern Metamorphic Belt—Exposed southeast of the park in the Devils Postpile quadrangle. JTRu: primary textures and structures are generally well preserved south of Garnet Lake. JTRc: Rocks composing the sedimentary lentil near Minaret Summit contain a much smaller proportion of volcanic material than most sedimentary rocks in the metavolcanic sequence.</td><td rowspan="7">Rise of the Batholith—Volcanic rocks of Shadow Creek and Mammoth Crest are approximately 5,000 m (16,000 ft) thick. JTRqa is a metamorphosed, previously kaolinite-bearing alteration zone. Fossil bivalves and ammonites of Early Jurassic age were found in JTRc about 2,600 m (8,500 ft) stratigraphically above the base of the section. Some of the metavolcanic sequence below this bed may be Triassic. A suite of samples collected approximately 900–1,200 m (3,000–4,000 ft) above the base have rubidium-strontium whole-rock ages of 230–265 million years, indicating that some rocks in the lowest part of this sequence may be as old as Permian. These units, however, are considered to be Triassic (?) and Jurassic pending further corroborative evidence. JTRx: most layers originated as ash flows.</td></tr>
<tr><td>JTRpz: piedmontite-bearing zone.</td></tr>
<tr><td>JTRqa: quartz-andalusite-corundum rock.</td></tr>
<tr><td>JTRa: dark-gray meta-andesite and metabasalt in thin to thick flows and hypabyssal intrusives. Aphanitic to porphyritic with plagioclase phenocrysts; local quartz amygdules.</td></tr>
<tr><td>JTRx: gray crystal tuff, rhyolite to quartz latite in composition. Contains lithic fragments and feldspar. White and pink feldspar and small wispy dark patches, bent around crystals or lithic fragments.</td></tr>
<tr><td>JTRd: gray metadacite and meta-andesite. Massive porphyritic flows and hypabyssal intrusive rocks. locally amygdaloidal with quartz or calcite fillings.</td></tr>
<tr><td>JTRc: calcareous sedimentary rock. Thin-bedded tuffaceous sandstone and siltstone, commonly calcareous. Contains minor amounts of marble, slate, and conglomerate.</td></tr>
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Age	Simplified Map Unit (Symbol) *Overview Sheet 1*	Map Unit (Symbol) *Colored if present on Overview Sheet 2*	Geologic Description	Geologic Issues	Geologic Features, Processes and General Location	Geologic History
JURASSIC or TRIASSIC	Eastern Metamorphic Belt, Pre-Cretaceous Rocks (pKemb)	Shadow Creek and Mammoth Crest rocks (JTRu, JTRpz, JTRqa, JTRa, JTRx, JTRd, JTRc, JTRss)	**JTRss**: gray metasandstone, metasiltstone and slate. Contains andalusite and garnet and is aphanitic to fine-grained with thin laminations of quartz, plagioclase and amphibole.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Exposed southeast of the park in the Devils Postpile quadrangle. **JTRss**: primary texture generally well preserved but locally phyllitic.	**Rise of the Batholith**—Volcanic rocks of Shadow Creek and Mammoth Crest are approximately 5,000 m (16,000 ft) thick.
		Metavolcanic rocks of Silver Creek (JTRsc)	Extensively recrystallized metavolcanic rocks. Primary textures and structures are obscure or absent. Correlation with units exposed in the Ritter Range Pendant is uncertain.		**Eastern Metamorphic Belt**—Exposed east of the park in the Devils Postpile quadrangle. Well-developed foliation is the dominant structure with schist and gneiss as the most common rocks.	**Rise of the Batholith**—Crystal-lithic tuff was probably the chief parent rock type; a few mafic flows and calcareous epiclastic rocks formed a quantitatively minor part of the sequence.
TRIASSIC	Eastern Metamorphic Belt, Triassic Rocks (TRemb)	Saddlebag Lake area rocks (TRmi, TRso, TRft, TRrt, TRsc, TRrh)	**TRmi**: mafic hypabyssal intrusive rock. Probably of andesitic composition.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Exposed northwest of Saddlebag Lake, Tuolumne Meadows quadrangle.	**Rise of the Batholith**—Metamorphosed volcanic rock.
			TRso: altered biotite-hornblende monzonite. Probably hypabyssal and cogenetic with Triassic volcanic rocks.		**Eastern Metamorphic Belt**—Exposed along the southeastern, southern, and southwestern margins of Saddlebag Lake, Tuolumne Meadows quadrangle.	**Rise of the Batholith**—Rubidium-strontium whole-rock age of about 220 million years (Upper Triassic).
			TRft: mafic flows and tuff. Pebble conglomerate at the base of the unit is overlain by tuffaceous beds of intermediate composition. Mafic flows occur at the top of the unit.	None—Northwest-trending exposure lies west of Saddlebag Lake and enters the park north of Gaylor Peak, Tuolumne Meadows quadrangle.	**Eastern Metamorphic Belt**—Sedimentary layer overlain by igneous volcanic rocks.	**Rise of the Batholith**—Rubidium-strontium whole-rock age of about 224 million years (Upper Triassic).
			TRrt: light-gray rhyolite ash-flow tuff with many flattened pumice fragments. Phenocrysts of quartz and plagioclase.	None—This unit lies outside of the park boundaries.	**Eastern Metamorphic Belt**—Narrow, northwest-trending exposure between **TRft** and **TRsc**, west of Saddlebag Lake.	**Rise of the Batholith**—Rhyolitic ash flows.
			TRsc: tuffaceous sandstone, siltstone, and conglomerate. Lenses of rhyolite tuff are present in a few places. Flattened pebbles are identical with rock in Paleozoic strata down section to the east.	None Significant—Exposures in the park have a limited areal extent.	**Eastern Metamorphic Belt**—Northwest-trending exposure crosses into the park west of Tioga Lake, Tuolumne Meadows quadrangle.	**Rise of the Batholith**—Conglomerate lenses apparently were deposited in stream channels.
			TRrh: rhyolite tuff. Mostly bedded.	None—This unit is not exposed in the park.	**Eastern Metamorphic Belt**—Thin slivers exposed along the eastern edge of **TRsc**.	**Rise of the Batholith**—Volcanic eruptions of rhyolite.
PERMIAN	Eastern Metamorphic Belt, Permian/ Pennsylvanian Rocks (PPNemb)	Ritter Range roof pendant rocks (Phv, Pax, Ptx, Pbc, PPNhy, PPNmy)	**Phv**: quartzofeldspathic hornfels, calc-silicate hornfels, and volcanic flows.	None Significant—Limited areal extent within park boundaries. Rockfall potential on steeper slopes.	**Eastern Metamorphic Belt**—Northwest-trending, linear exposures that cross the eastern border of the park. Most exposures are located east of the park in the Mono Craters quadrangle.	**Assembling California**—Metamorphosed sedimentary and volcanic rocks of Permian age.
			Pax: andesite flows and breccias, local graywacke and sandstone lenses.			

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Age	Simplified Map Unit (Symbol) *Overview Sheet 1*	Map Unit (Symbol) *Colored if present on Overview Sheet 2*	Geologic Description	Geologic Issues	Geologic Features, Processes and General Location	Geologic History
PERMIAN	Eastern Metamorphic Belt, Permian/ Pennsylvanian Rocks (PPNemb)	Ritter Range roof pendant rocks (Phv, Pax, Ptx, Pbc, PPNhy, PPNmy)	**Ptx**: volcanic tuffs, volcanic flows, and local greywacke.	None Significant—Limited areal extent within park boundaries. Rockfall potential on steeper slopes.	**Eastern Metamorphic Belt**—Northwest-trending, linear exposures that cross the eastern border of the park. Most exposures are located east of the park in the Mono Craters quadrangle.	**Assembling California**—Metamorphosed sedimentary and volcanic rocks of Permian age.
			Pbc: local basal conglomerate.			
PERMIAN or PENNSYLVANIAN			**PPNhy**: pelitic and siliceous hornfels. Moderately well-bedded dark siliceous hornfels and small amounts of interbedded pelitic hornfels, slate, and quartzite.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Minor exposures east of the park in the Devils Postpile quadrangle. **PPNmy** contains crinoid fossils. The two **PPNmy** outcrops are separated by massive tuffaceous conglomerate that contains many marble fragments.	**Assembling California**—Age tentatively assigned to Permian or Pennsylvanian.
			PPNmy: gray marble in two small outcrops north of Minaret Summit.			
		Gull Lake roof pendant rocks (PPNhcl, PPNmgl, PPNq, PPNc)	**PPNhcl**: quartzofeldspathic hornfels.	**Preservation of the Geologic Landscape**—historic mine complex is present.	**Eastern Metamorphic Belt**—Exposed in the Mono Craters quadrangle.	**Assembling California**—Age tentatively assigned to Permian or Pennsylvanian.
			PPNmgl: carbonaceous marble.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Exposed east of the park primarily in the Mono Craters quadrangle. **PPNhcl** crosses the eastern boundary of the park, but most exposures lie east and southeast of the border.	**Assembling California**—Age tentatively assigned to Permian or Pennsylvanian.
			PPNq: hornfels, quartzite, and quartzofeldspathic hornfels.			
			PPNc: marble and calc-silicate hornfels.			
		Twin Peak sequence (PPNhtp, PPNmtp, PPNqz)	**PPNhtp:** brown, green, greenish-gray, and gray calc-silicate and quartzofeldspathic hornfels, biotite schist, and marble.	**Rockfall**—Rockfall potential on the steeper slopes near Virginia Peak, but these backcountry exposures pose no significant geologic issues for the park.	**Eastern Metamorphic Belt**—Exposed near Virginia Peak in the Matterhorn Peak quadrangle, northern border of the park. **PPNmtp** contains garnet, epidote, and wollastonite.	**Assembling California**—The sequence is approximately 900 m (3,000 ft) thick and similar to the rocks of the Ritter Range and Gull Lake pendants. Age tentatively assigned to Permian or Pennsylvanian.
			PPNmtp: light-gray and buff-colored, massive to poorly bedded, fine- to medium-grained crystalline marble.			

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Age	Simplified Map Unit (Symbol) *Overview Sheet 1*	Map Unit (Symbol) *Colored if present on Overview Sheet 2*	Geologic Description	Geologic Issues	Geologic Features, Processes and General Location	Geologic History
PERM. or PENNSY.	Eastern Metamorphic Belt, Permian/ Pennsylvanian Rocks (PPNemb)	Twin Peak sequence (PPNhtp, PPNmtp, PPNqz)	**PPNqz:** light- to medium-gray and brown, massive to layered quartzite, quartzofeldspathic hornfels, and metaconglomerate.	**Rockfall**—Rockfall potential on the steeper slopes near Virginia Peak, but these backcountry exposures pose no significant geologic issues for the park.	**Eastern Metamorphic Belt**—Exposed near Virginia Peak in the Matterhorn Peak quadrangle, northern border of the park.	**Assembling California**—The sequence is approximately 900 m (3,000 ft) thick and similar to the rocks of the Ritter Range and Gull Lake pendants. Age tentatively assigned to Permian or Pennsylvanian.
SILURIAN or ORDOVICIAN	Eastern Metamorphic Belt, Silurian/ Ordovician Rocks (SOemb)	Ritter Range roof pendant rocks (SOhm, SOsm)	**SOhm**: dark-colored, bedded to massive hornfels. Local beds of silicate marble.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Exposed east of the park in the Devils Postpile quadrangle. **SOhm** contains plagioclase, tremolite, diopside, and wollastonite as well as minor amounts of quartzite.	**Assembling California**—Age tentatively assigned to Silurian or Ordovician. Parent rocks of **SOhm** were shale, siltstone, marly siltstone, and quartz-bearing limestone.
SILURIAN or ORDOVICIAN	Eastern Metamorphic Belt, Silurian/ Ordovician Rocks (SOemb)	Ritter Range roof pendant rocks (SOhm, SOsm)	**SOsm**: massive to poorly layered silicate marble.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Exposed east of the park in the Devils Postpile quadrangle. **SOhm** contains plagioclase, tremolite, diopside, and wollastonite as well as minor amounts of quartzite.	**Assembling California**—Age tentatively assigned to Silurian or Ordovician. Parent rocks of **SOhm** were shale, siltstone, marly siltstone, and quartz-bearing limestone.
SILURIAN or ORDOVICIAN	Eastern Metamorphic Belt, Silurian/ Ordovician Rocks (SOemb)	Log Cabin Mine roof pendant rocks (SOm, SOq, SOa, SOx, SOc, SOh, SOs)	**SOm**: marble and calc-silicate hornfels.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Exposed west of Mono Lake and east of the park in the Mono Craters quadrangle.	**Assembling California**—Age tentatively assigned to Silurian or Ordovician.
SILURIAN or ORDOVICIAN	Eastern Metamorphic Belt, Silurian/ Ordovician Rocks (SOemb)	Log Cabin Mine roof pendant rocks (SOm, SOq, SOa, SOx, SOc, SOh, SOs)	**SOq**: biotite-bearing quartzite.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Exposed west of Mono Lake and east of the park in the Mono Craters quadrangle.	**Assembling California**—Age tentatively assigned to Silurian or Ordovician.
SILURIAN or ORDOVICIAN	Eastern Metamorphic Belt, Silurian/ Ordovician Rocks (SOemb)	Log Cabin Mine roof pendant rocks (SOm, SOq, SOa, SOx, SOc, SOh, SOs)	**SOa**: older metasedimentary rocks, hornfels.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Exposed west of Mono Lake and east of the park in the Mono Craters quadrangle.	**Assembling California**—Age tentatively assigned to Silurian or Ordovician.
SILURIAN or ORDOVICIAN	Eastern Metamorphic Belt, Silurian/ Ordovician Rocks (SOemb)	Log Cabin Mine roof pendant rocks (SOm, SOq, SOa, SOx, SOc, SOh, SOs)	**SOx**: older metasedimentary rocks, quartzite.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Exposed west of Mono Lake and east of the park in the Mono Craters quadrangle.	**Assembling California**—Age tentatively assigned to Silurian or Ordovician.
SILURIAN or ORDOVICIAN	Eastern Metamorphic Belt, Silurian/ Ordovician Rocks (SOemb)	Log Cabin Mine roof pendant rocks (SOm, SOq, SOa, SOx, SOc, SOh, SOs)	**SOc**: marble, calc-silicate hornfels, and quartzite.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Exposed west of Mono Lake and east of the park in the Mono Craters quadrangle.	**Assembling California**—Age tentatively assigned to Silurian or Ordovician.
SILURIAN or ORDOVICIAN	Eastern Metamorphic Belt, Silurian/ Ordovician Rocks (SOemb)	Log Cabin Mine roof pendant rocks (SOm, SOq, SOa, SOx, SOc, SOh, SOs)	**SOh**: quartzofeldspathic hornfels.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Exposed west of Mono Lake and east of the park in the Mono Craters quadrangle.	**Assembling California**—Age tentatively assigned to Silurian or Ordovician.
SILURIAN or ORDOVICIAN	Eastern Metamorphic Belt, Silurian/ Ordovician Rocks (SOemb)	Log Cabin Mine roof pendant rocks (SOm, SOq, SOa, SOx, SOc, SOh, SOs)	**SOs**: marble and calc-silicate hornfels.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Exposed west of Mono Lake and east of the park in the Mono Craters quadrangle.	**Assembling California**—Age tentatively assigned to Silurian or Ordovician.
PALEOZOIC ERA	Eastern Metamorphic Belt, Paleozoic Rocks (PZemb)	Metasedimentary strata (PZms)	Quartzofeldspathic hornfels, calc-silicate hornfels, and carbonaceous marble.	None—These units lie outside of the park boundaries.	**Eastern Metamorphic Belt**—Exposed east of the park in the northeast corner of the Tuolumne Meadows quadrangle.	**Assembling California**—Age assigned to the Paleozoic.

Map Unit Properties Table B: Yosemite Valley Glacial and Postglacial Deposits, Yosemite National Park

Colors in Map Unit column correspond to Geologic Map Overview sheets 3 and 4. Bold text corresponds to sections of the report.
Surficial and glacial units are also included in the compiled bedrock and surficial map for Yosemite National Park. Refer to Map Unit Properties Table A.

Age	Map Unit (Symbol) *Sheets 3 and 4*	Geologic Description from Matthes (1930)	Geologic Issues	Geologic Features and Processes and General Location	Geologic History
QUATERNARY (Recent)	Granite Sand (Qag)	Granite sand washed into valleys and basins; bars in river channel	**Debris Flow and Flooding**—Overbank and floodplain deposits represent flood and debris-flow events.	**Recent Geomorphic Features (Fluvial)**—Meandering channel patterns, point bars, cutbanks, terraces, floodplains, and debris deposited during flooding.	**Tension, Uplift, and Ice**—These unconsolidated units in Yosemite National Park represent recent fluvial deposition, flooding, and mass-wasting processes.
	River-Borne Sand (Qar)	River-borne sand and gravel filling glacial-lake basins			
	Fans (Qaf)	Fans, mostly of coarse rock waste, produced by torrent action		**Recent Geomorphic Features (Fluvial)**—Fans deposited primarily where streams spill out onto valley floor.	
	Rock Waste (Qts)	Rock waste shed from cliffs	**Rockfalls, Rockslides and Rock Avalanches**—These mass-wasting deposits represent unpredictable movement of rock material from unstable slopes. They are hazards that affect visitor safety and park infrastructure (i.e., roads, trails, buildings, sewer lines, campgrounds). Triggering mechanisms vary.	**Talus Piles—**Large talus piles have formed beneath cliffs.	
QUATERNARY (Pleistocene)	Wisconsin Stage Individual Moraines (Qwmi)	Individual moraines	**Erosion**—Glacial deposits may form unstable slopes.	**Pleistocene Glacial Features (Depositional)**—Moraines. Qwmi comprises Bridalveil Moraine.	**Tension, Uplift, and Ice**—Moraines deposited by glaciations during the Wisconsin glaciation as described by Matthes (1930). The "Wisconsin stage" terminology is no longer in use. The deposits represent Tioga (26,000-18,000 years ago) and Tahoe (140,000-80,000 years ago) glaciations.
	Wisconsin Stage Morainal Material in Sheets (Qwms)	Morainal material in sheets; some of it washed and redeposited		**Pleistocene Glacial Features (Depositional)**—Moraines. Primarily mapped near Yosemite Creek and Little Yosemite Valley.	
	Wisconsin Stage Scattered Morainal Material (Qws)	Scattered morainal material			
	Wisconsin Stage Glacial Outwash (Qwo)	Glacial outwash in front of moraines		**Pleistocene Glacial Features (Depositional)**—Outwash. Mapped west of El Capitan Meadow to Pahono Bridge, near Bridalveil Moraine.	**Tension, Uplift, and Ice**—Outwash flowed out of glaciers, beyond moraines deposited by glaciations during the Tioga (26,000-18,000 years ago) and Tahoe (140,000-80,000 years ago) glaciations, referred collectively as the Wisconsin stage by Matthes (1930).
	Wisconsin Stage Limits of Ice (Qwx)	Approximate limits of area covered by ice of Wisconsin stage		**Pleistocene Glacial Features—**Encompasses a variety of erosional (e.g., U-shaped valleys) and depositional glacial features (e.g., till, moraines, outwash).	**Tension, Uplift, and Ice**—Reflects the maximum extent of glaciers during the Tioga (26,000-18,000 years ago) and Tahoe (140,000-80,000 years ago) glaciations, referred collectively as the Wisconsin stage by Matthes (1930).
	El Portal Stage Individual Moraines (Qemi)	Individual moraines (crests shown by rows of dots)		**Pleistocene Glacial Features (Depositional)**—Moraines. Mapped at higher elevations than Qwmi.	**Tension, Uplift, and Ice**—Moraines deposited during the El Portal stage as described by Matthes (1930). The "El Portal stage" terminology is no longer used. The deposits likely correspond to a pre-Tahoe glaciation.

Colors in Map Unit column correspond to Geologic Map Overview Sheets 3 and 4. Bold text corresponds to sections of the report.
Surficial and glacial units are also included in the compiled bedrock and surficial map for Yosemite National Park. Refer to Map Unit Properties Table A.

Age	Map Unit (Symbol) *Sheets 3 and 4*	Geologic Description from Matthes (1930)	Geologic Issues	Geologic Features and Processes and General Location	Geologic History
QUATERNARY (Pleistocene)	El Portal Stage Morainal Material in Sheets (Qems)	Morainal material in sheets; some of it washed and re-deposited	**Erosion**—Glacial deposits may form unstable slopes..	**Pleistocene Glacial Features (Depositional)**—Moraines. Mapped at higher elevations than Qwms.	**Tension, Uplift, and Ice**—Moraines deposited during the El Portal stage as described by Matthes (1930). The "El Portal stage" terminology is no longer used. The deposits likely correspond to a pre-Tahoe glaciation.
	El Portal Stage Scattered Morainal Material (Qes)	Scattered morainal material		**Pleistocene Glacial Features (Depositional)**—Moraines. Mapped at higher elevations than Qws.	
	El Portal Stage Gravel Deposits (Qeg)	Gravel deposited in ice-dammed lake		Deposited in Illilouette Creek valley above Illilouette Falls.	**Tension, Uplift, and Ice**—During the a pre-Tahoe glaciation ("El Portal stage" of Matthes 1930), an ice dam formed in Illilouette Creek valley. Gravel was subsequently deposited in the lake that formed behind the dam.
	El Portal Stage Limits of Ice (Qex)	Approximate limits of area covered by ice of El Portal stage		**Pleistocene Glacial Features**—Encompasses a variety of erosional (e.g., U-shaped valleys) and depositional glacial features (e.g., till, moraines). Glacial erratics from El Portal and Glacier Point stages mapped throughout Qex.	**Tension, Uplift, and Ice**—Reflects the maximum extent of glaciers during a pre-Tahoe glaciation.
	Glacier Point Stage Limits of Ice (Qgx)	Approximate limits of area covered by ice of Glacier Point stage		**Pleistocene Glacial Features**—Encompasses a variety of erosional (e.g., U-shaped valleys) and depositional glacial features (e.g., till, moraines). Glacial erratics from Glacier Point stage mapped throughout **Qgx**.	**Tension, Uplift, and Ice**—Reflects the maximum extent of glaciers during a pre-Tahoe glaciation. Matthes (1930) interpreted these deposits as the oldest glaciation evident in Yosemite Valley.
CRETACEOUS-JURASSIC	Un-glaciated Deposits (ung)	Rock not covered by the ice	**Rockfall**—a potential issue for all bedrock exposed on steep slopes throughout Yosemite Valley.	**Nunataks**—Peaks that reached above glaciations include El Capitan, Half Dome, and Eagle Peak. Additional features and processes are listed for bedrock geologic map units such as **Khd** (Half Dome granodiorite) and **Kec** (El Capitan Granite).	**The Rise of the Batholith**—Bedrock units are primarily intrusive granitic rocks of Cretaceous or Jurassic-Cretaceous age. Refer to Map Unit Properties Table A for more information.
	Bare Rock, Missing Glacial Material (bedrock)	These are areas of bare rock devoid of morainal material that were most likely glaciated at one time	**Rockfall**—a potential issue for all bedrock exposed on steep slopes throughout Yosemite Valley. **Protection of Glacial Features**—glacial polish, striations, percussion marks, crescent gouges, chatter marks, and subglacial water polish may be present. They can be damaged or destroyed via natural weathering processes or vandalism.	**Pleistocene Glacial Features (erosional)**—Encompasses a variety of erosional features (e.g. walls of U-shaped valleys).	**The Rise of the Batholith**—Bedrock units are primarily intrusive granitic rocks of Cretaceous or Jurassic-Cretaceous age. Refer to Map Unit Properties Table A for more information. **Tension, Uplift, and Ice**—Glaciers from one or more glaciations covered these units.

Source map: Matthes, F. E. 1930. Map of glacial and postglacial deposits in Yosemite Valley, Mariposa County, California.
Plate 29 *in* F. E. Matthes. 1930. Geologic history of Yosemite Valley. US Geological Survey. Professional Paper 160.