Interpreting Geology in Yosemite National Park: A Monument to Strong Granite, Powerful Glaciers, and the Perseverance of Life

by
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Preface (by Sarah E. Dunham)

“There is a great deal of talk these days about saving the environment. We must ... for the environment sustains our bodies. But as humans we also require support for our spirits ... and this is what certain kinds of places provide.

“The catalyst that converts any physical location – any environment if you will – into a place, is the process of experiencing deeply. A place is a piece of the whole environment that has been claimed by feelings. Viewed simply as a resource that sustains our humanity, the earth is a collection of places.

“We never speak, for example, of an environment we have known; it is always places we have known – and recall. We are homesick for places, we are reminded of places. It is the sounds, the smells and sights of places which haunt us against which we often measure our present.”

(Alan Gussow, A Sense of Place: Washington, DC, Friends of the Earth, 160p., 1972)

Yosemite is a special place. When visitors claim Yosemite with their feelings, it becomes theirs. One of my most vivid memories of my three seasons in Yosemite is standing on the summit of Mt. Hoffman and looking around me. The sight emblazoned in my memory includes jagged granite drop-offs and string-of-pearl alpine meadows clinging to life set against a gray granite backdrop. Whether behind the desk in the Visitor Center or out roving, my amazement and enthusiasm for Yosemite never waned. Your challenge as a ranger is to capture the interest of visitors and help them claim Yosemite and its geology with their feelings.

Every visitor will experience geology during his or her visit to the park. The purpose of this manual is to help the interpretive staff convey geologic principles and the “story behind the scenery” to park visitors. Basic geologic concepts and the results of the latest research on local and regional levels are incorporated in ways that are understandable for a non-geologist audience. Chapter 1 is an overview of interpretive methods, with emphasis on ways to connect visitors to the geologic processes responsible for the spectacular landscape of Yosemite National Park (YNP). Chapter 2 is an introduction to plate tectonic processes that formed the rocks and scenery of YNP. It emphasizes regional processes such as subduction, granite formation, and uplift. Chapter 3 uses climate change to link landforms in YNP to the glacial processes that sculpted them. This includes a discussion of the Earth’s “Milankovitch Cycles” and their influence on Yosemite’s glacial history. Examples of different landforms in YNP are used to illustrate the effects of glacial erosion. Chapter 4 focuses on the link between geology and the flora and fauna in Yosemite. There is an emphasis on weathering, erosion, and subsequent transport and deposition to form habitat. Chapter 5 focuses on the link between geology and people. It expands on the processes introduced in the previous three chapters through a discussion of the Yosemite Indians, sheepherding, mining, rock climbing, and current visitors in YNP.

Each chapter includes text boxes concentrating on supplemental information, interpretive methods, and tangible-intangible connections that can be used by the YNP staff. I have included methods that I utilized in my three summers as an...
Interpretive Ranger in Yosemite Valley, as well as methods that have been used by other YNP staff.

It is my hope that park rangers will be able to use this manual as a reference in preparing interpretive programs. Yosemite’s landscape is one of California’s and Earth’s most famous icons. As research into the geology and other aspects of the region continues, rangers and visitors to Yosemite National Park can all increase their understanding and appreciation of this awesome landscape.
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Chapter 1

Helping Visitors Discover Geology in Yosemite National Park

On June 30, 1864, Abraham Lincoln signed the Yosemite Grant. The grant deeded Yosemite Valley and the Mariposa Grove of Giant Sequoias to the state of California, setting those places aside as a “nature preserve.” Although this event went largely unnoticed by a nation in the midst of civil war, the Yosemite Grant is significant. It was the first time in United States history that land was set aside by the federal government for preservation and public use.

Yosemite National Park is a monument to strong granite, powerful glaciers, and the perseverance of life. Most people who visit Yosemite National Park are drawn there for one reason: Yosemite is beautiful. A big part of your job as an interpreter in Yosemite National Park is to inspire visitors to care about the park and its resources.

Geology-Oriented Interpretation

One of Yosemite’s most unique resources is its landscape. A dictionary definition of the word “landscape” refers to all the visible features of an area of Earth’s surface. Often landscape is used to describe scenery, or the aesthetic appeal inherent in nature. But the word landscape means different things to different people. Whatever your definition of landscape, geology is the foundation. Every visitor to Yosemite will experience geology first-hand because they will marvel at and walk on the landscape.

The science of geology is divided into a variety of different specialties, many of which are relevant in Yosemite. Plate tectonics studies the movement of rigid plates comprising the surface and outer hard shell of the Earth. Plate tectonic theory investigates the development of mountain ranges like the Sierra Nevada, and helps us understand why rocks that formed long ago deep underneath Earth’s surface are now visible 10,000 feet (3,000 meters) above sea level! Petrology studies the origin and formation of rocks including igneous rocks that cooled from liquid. Petrologists ask the questions: Where did the rock material originate? When did the liquid rock cool to form the solid rock we see today? What happened while the rock was cooling? Glaciology is the study of the movement of glacial ice and its effects on the landscape. Glaciologists ask the questions: How and when did ice move over Earth’s surface? What effects did ice movement have on Earth’s surface? Finally geomorphology investigates tectonic and erosional processes that shape Earth’s surface. Geomorphologists ask the question: Why does Earth’s surface look the way it does?

Many of these geological questions are explored in the exhibits in the Valley Visitor Center. The five main exhibit sections explore the interconnections between geological, hydrological, biological, and cultural processes over millions of years. As an interpreter, you can go beyond the exhibits and utilize the landscape to share the “story behind the scenery.” This manual is a toolbox to help interpreters expand their knowledge base of Yosemite’s geology and to discover some of the connections between geology and the varied aspects of Yosemite’s landscape.

Connecting Yosemite’s Visitors to Yosemite’s Landscape

In order to create opportunities for visitors to discover their own connections to the meanings of Yosemite National Park, rangers must be able to communicate their knowledge of the Park to their audiences in meaningful ways. The National Park Service (NPS) interpretive equation sums up how this might be accomplished:

\[(Kr + Ka) \times AT = IO\]

where:
- \(Kr\) = Knowledge of the Resource
- \(Ka\) = Knowledge of the Audience
- \(AT\) = Appropriate Technique
- \(IO\) = Interpretive Opportunity

This manual seeks to increase knowledge of Yosemite National Park (the resource) through the discussion of basic geologic processes and the dissemination of the results of the latest scientific research. It encourages park rangers to think about Yosemite’s visitors (the audience) and the methods...
(techniques) that they can use to create interpretive opportunities by relating geological features and processes as part of the Yosemite landscape – the “scenery” that visitors come to the park to see and enjoy!

In the summer of 2005 a visitor survey was conducted to find out more about Yosemite’s visitors by answering questions such as: How old are visitors? How many times have they come to the park? What did they do during their time in Yosemite? The majority of Yosemite’s visitors are families from California visiting the park for the first time and staying for 2 to 3 days. Adults tend to be educated; over 50% have an undergraduate or graduate college degree. Interpreters should also consider what the audience brings with them to programs via questions such as: What are the visitors’ expectations and interests? What existing attitudes do they bring to the park?

Appropriate technique varies depending on the program and the audience. Every program should have a theme. A theme conveys a central idea, which interpreters can structure information around. It should encompass the major topic of the program; link tangible features that visitors observe to intangible meanings, ideas, and concepts; and answer the question, “So what?” Using a theme helps to put information in context, thus making it more relevant to visitors. Visitors commonly remember ideas and compelling stories, so it is important to relate concepts back to larger, thematic ideas during a program.

We live, love, and die on the Earth, so everything in life relates in some fashion to geology. But don’t try to do it all at once – a program that seeks to relate ALL the geology in Yosemite is doomed to fail. It also helps to recognize that geology needn’t be conveyed only via geology programs. Existing programs focused on Yosemite’s biology, ecology, human history, or climate might benefit from consideration of the broader landscape that is formed and modified by geological processes. In fact, such programs might prove even more effective in educating the public on geology, as the geology might be seen by visitors in the context of topics they are more familiar with, and perhaps more passionate about. Use your own excitement and passion to ignite curiosity in others. If there’s some flammable stuff there, it will catch fire!
Chapter 2
Forming the Foundation: Plate Tectonics

Earth’s surface isn’t all one piece. It’s broken into at least 15 pieces called tectonic plates (Figure 2.1). These solid plates make up the hard outer shell called the lithosphere (Figure 2.2). The lithosphere is composed of the crust (the outer surface we walk on) and the outermost part of the mantle (the intermediate layer of Earth’s interior, Figure 2.3). The plates move at about the rate your fingernails grow. Because the plates are moving, their boundaries are places where much of the action takes place — earthquakes, volcanoes, and the formation of mountain ranges like the Sierra Nevada!

Why do the plates move? As you go deeper into the Earth, it gets hotter, causing solid material in part of the mantle to soften. The layer of softened mantle is called the asthenosphere. The rigid plates of lithosphere move over this weaker layer. The rise in temperature also causes the asthenosphere to expand and flow upward in places. Eventually it cools and begins to sink. This process creates a convection cell. The motion in a convection cell is very similar to a pot of boiling French Onion soup. When the soup is at a full rolling boil, the hot soup near the burner rises to the top where the heat is released. Like the cheesy crust on top of the soup, the overlying plates of lithosphere ride along over the convecting asthenosphere. Earthquakes, volcanoes, and mountain ranges typically occur where the plates interact along their boundaries (Figure 2.4).

Figure 2.1. Earth’s hard outer shell (lithosphere) is broken into moving tectonic plates. In the not-too-distant geologic past, the Yosemite region was the site of volcanic activity at a convergent plate boundary, much as the Pacific Northwest and western South America are today. Yosemite currently “feels” some of the effects of the Pacific Plate sliding in a northwesterly direction along a transform plate boundary – the San Andreas Fault in California. (Modified from Lillie, 2005.)
Visitors sometimes have a hard time visualizing how the character of the Earth changes below the surface we walk on. Geologists characterize layers in the Earth in two ways (Figure 2.2). There are three layers that differ greatly in chemical composition (left side of Figure 2.2): A very dense core, made mostly of the elements iron and nickel; the mantle, made up of minerals (aggregates of elements) that are rich in iron and magnesium; and the crust, made up of lighter minerals that are rich in silica, including quartz and feldspar.

The three compositional layers can be demonstrated using a Peanut M&M®. Bite through half the M&M® so you can see all the layers. The peanut is the core, the chocolate is the mantle, and the candy coating is the crust (Figure 2.3).

The physical states of these three layers change because Earth’s temperature and pressure both increase with depth. This leads to the five layers shown on the right side of Fig. 2.2 (lithosphere, asthenosphere, lower mantle, outer core, and inner core).
There are three types of plate boundaries characterized by the way plates move relative to each other: divergent, where plates pull apart and new lithosphere is formed (for example, the Mid-Atlantic Ridge); convergent, where one plate is forced underneath the other and lithosphere is recycled (the Coastal Ranges and Cascade Mountains in the Pacific Northwest), and transform where plates grind against each other and lithosphere is neither created nor destroyed (the San Andreas Fault) (Figure 2.4).

Yosemite National Park was born in a subduction zone 245 million years ago, when the ancient Farallon Plate began subducting under the North American Plate (Figure 2.5. Ocean sediments (sand, mud, and fossil remains of animals) were scraped off the top of the Farallon Plate and piled up, forming islands and coastal mountain ranges at the edge of the continent. Over time some of the sedimentary rocks were pushed (subducted) deeply into the Earth, where they experienced high heat and pressure, forming the layered

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**Figure 2.4.** The three types of plate boundaries can be demonstrated using Oreo Cookies®! (“Double Stuf” works the best.) The upper cookie is the rigid lithosphere and the creamy filling is the plastic asthenosphere. First you’ll need to twist off one of the cookies and crack it in two pieces. Divergent plate boundaries (a) are characterized by volcanoes and small, shallow earthquakes as the plates move away from each other. New lithosphere is formed as the asthenosphere wells up between the two plates to fill the gap. This happens at the Mid-Atlantic Ridge and in the Basin and Range Province in the western United States. To demonstrate a convergent plate boundary (b), shove one of the cookie halves under the other. You’ll see one of the plates (cookies) dives down through the asthenosphere (creamy filling). This process is called subduction. The grinding sound you hear as the cookies rub together represents earthquakes. The Cascadia Subduction Zone in the Pacific Northwest is an example of a convergent plate boundary. Transform plate boundaries occur where two plates slide past each other. They usually lack volcanoes but are characterized by shallow earthquakes. An example of a transform plate boundary most visitors are familiar with is California’s San Andreas Fault. (Modified from Lillie, 2005.)
Figure 2.5: Central California is an example of an ancient subduction zone. A plate capped by thin oceanic crust (Farallon Plate) subducted beneath a plate capped by thicker, more buoyant continental crust (North American Plate), forming a chain of volcanoes. (See Figure 2.6 for a diagram of a magma chamber). Some of the magma undoubtedly erupted on the surface but the resulting volcanic rocks have mostly eroded away. (Modified from Lillie, 2005).

black, green, and red **metamorphic rocks** found in Yosemite’s foothills and high country. These rocks comprise only 5% of the Park’s exposed rocks, but they are spectacular. You can walk on a 245 million year old beach that is now almost 10,000 feet (3,000 meters) above sea level!

**Quick Yosemite Volcano Q+A:**

No way! **There were volcanoes in Yosemite?**
Way! Geologists think the ancient Sierra Nevada looked similar to the Andes Mountains, a chain of **composite volcanoes** in South America. So far, geologists have been unable to decipher the details of the ancient Sierra eruptions because most of the original volcanic evidence has eroded away.

So what do the rocks in Yosemite tell us about the volcanoes in the region?
There are about four different rock types that form a “concentric kidney bean” pattern. These rocks are part of the Tuolumne Intrusive Suite (TIS) that formed between about 95 and 85 million years ago. Similar concentric patterns occur underneath groups of volcanoes in the Andes Mountains of South America.

**Does each layer correspond to an eruption?**
No. New research suggests that each rock type formed near the end of a distinct period of high intrusive (and possibly volcanic) activity. During these distinct periods multiple **dikes** introduce small amounts of liquid into the surrounding **country rock**. These dikes ascended through conduits in the crust formed by a weakness in the country rock or along the path of a previous dike. This liquid solidified in a short period of time. Over time these small amounts of magma merged to form a large, continuous body of rock. If the magma and the country rock were hot enough, it would be possible to form a large magma chamber (Figure 2.6b). This chamber could have produced explosive volcanic eruptions.

**Do geologists know if the volcanoes erupted at all?**
It is likely that the **vents** in the Yosemite region did produce at least one explosive eruption. The Johnson Granite **Porphyry** has been interpreted as the remnant of an explosive eruption and field relations at the remains of the Minarets Caldera record at least one episode of caldera collapse that could have coincided with an explosive volcanic eruption.

Making Mountains: Volcanoes of the Ancient Sierra Nevada

As the Farallon Plate subducted deeper and deeper, it got hotter and hotter. Eventually the Farallon Plate was so hot it started to dehydrate, or
“sweat,” releasing water from the ocean sediments and hard rock on top of the plate. Water lowered the melting point of some of the minerals in the North American Plate, causing the plate to partially melt and form basalt magma. The magma rose because it is more buoyant than the surrounding rock. Silica-poor minerals began to crystallize as the magma cooled, leaving a silica-rich magma that rose higher in the crust (Figures 2.6 and 2.7). Yosemite’s granite-type rocks are the product of the rising and cooling of silica-rich magma, which crystallized in the upper portion of the crust as plutons comprising the Sierra Nevada Batholith. Some of the distilled magma erupted onto Earth’s surface and formed volcanoes. The Sierran volcanoes were active from about 220 to 80 million years ago and probably looked similar to the Andes Mountains in South America where the Nazca Plate is subducting under the South American Plate (Figure 2.1).

What happened to the volcanoes? The Farallon Plate was being created at a mid-ocean ridge in the Pacific Ocean, but the plate was being subducted faster than it was being created (Figure 2.8a). This meant that volcanism and plutonism in the Sierra Nevada Region would eventually cease because the subduction zone consumed the Farallon Plate in the California region (Figure 2.8b). Note that subducting remnants of the Farallon Plate still exist, namely the Cocos Plate to the south and the Juan de Fuca Plate to the north (Figure 2.8c). The youngest igneous rocks found in Yosemite are about 80 million years old, suggesting the volcanoes “turned off” around that time. The remaining magma that was feeding the volcanoes cooled completely. The Sierra Nevada Batholith is the great mass of all the plutonic rocks in the region that formed over tens of millions of years of subduction. (Most of Yosemite’s granites formed from 105 to 88 million years ago). Yosemite’s rocks thus represent the underlying “plumbing” of volcanoes. The Sierra Nevada Batholith is the master plumbing system of a whole region of volcanoes. When magma solidifies within the crust, the overlying rock acts like a blanket insulating the magma. As a result, the magma crystallizes slowly as large mineral crystals grow over thousands of years.

While the magma was cooling, the forces of ice and water began to weather and erode away the
overlying volcanoes, stripping the blanket off. The rock fragments from the volcanoes were carried into California’s Central Valley. These layers of sediment form the soil that supports agriculture in the region.

By 29 million years ago, the Central California portion of the Farallon Plate had completely subducted. For the first time off the coast of California, the Pacific Plate and the North American Plate were in direct contact with each other. But in California the Pacific Plate does not subduct under the North American Plate, it slides laterally northward. This grinding motion formed a transform plate boundary called the San Andreas Fault.

During this time, the Basin and Range Province of the western US began to rift apart. Faults developed, producing a series of parallel mountain ranges and valleys as the region stretched apart. The land on the east side of Yosemite National Park drops down abruptly along a steep fault escarpment on the western edge of the Basin and Range Province. It is likely that the regional joints in the Sierra Nevada also formed around this time to accommodate the different stress pattern in the rock.

**What do Rocks and Legos® Have in Common?**

A rock can be compared to a castle built out of different colored Legos®, the mineral crystals are the individual Legos® that make up the rock/castle. Minerals are made up of elements put together in an ordered structure, similar to the distinctively shaped Legos® chosen for construction of the castle. (Figure 2.7). Geologists use the kinds and amounts of minerals in the rocks to classify them.

The different colored minerals in Yosemite’s rocks are often referred to as “salt and pepper” flecks. “Pepper” flecks in the rocks are dark minerals called biotite and hornblende. Biotite crystals are brown to black sheets that can be split apart with your finger or a knife. Well-formed biotite crystals are 6-sided (hexagonal) but they don’t always form that way. Hornblende is dark green to almost black and commonly occurs as small, rod-shaped crystals. It also has lines called striations, formed from the crystal breaking along two flat sides. These flat sides, called planes, make the crystals appear like charcoal if you look closely. These dark minerals are rich in the elements iron (Fe) and magnesium (Mg) and are lower in silica (SiO₂) than the other minerals in the rocks. The minerals that have more silica are the “salt” in the rocks, namely feldspar and quartz. Feldspar crystals are usually translucent or opaque, and are creamy or pink in color. Well-formed crystals are rectangular (there are awesome rectangular feldspar crystals in the Cathedral Peak Granodiorite along the trail from Sunrise to Cathedral Lake). Feldspar crystals break along flat planes (geologists call these planes cleavage planes) so sometimes you can see the sun glint off them. Quartz is the last mineral to crystallize as the magma rises toward the surface. It is translucent and can be anywhere from clear (looking like crushed ice) to dark gray. It breaks like glass, so sometimes you can see small, curved surfaces with a magnifying glass.

**Figure 2.7.** An element is a form of matter that cannot be chemically converted or broken down into a simpler form. When elements combine they make minerals. For example, the elements silicon and oxygen combine to make the mineral quartz. A molecule is a compound of at least two atoms held together by bonds between the atoms. Mineral molecules are characterized by an orderly arrangement of atoms. This orderly arrangement can be seen in biotite’s thin sheets, hornblende’s stringy appearance, feldspar’s rectangular crystals, and quartz’s six facets and pointed tip.
Figure 2.8. Subduction of the Farallon Plate beneath of the North American Plate created a chain of volcanoes extending from Alaska to Mexico. (A) As subduction continued, the mid-ocean ridge system separating the Farallon and Pacific plates approached North America. (B) A transform plate boundary developed along the edge of North America when the ridge system reached the subduction zone. The subduction stopped, shutting off the volcanoes. During this time, the Basin and Range Province (a zone of continental rifting that includes the east side of Yosemite N.P.) also began to develop. (C) Subduction continues today north and south of the transform plate boundary (San Andreas Fault) – the Cocos and Juan de Fuca Plates are remnants of the Farallon Plate. (D) Modern elements of the Cascades volcanic chain in California include Mt. Shasta and Lassen Peak. The intrusive igneous rocks of Yosemite NP and the Sierra Nevada are the remains of magma chambers that once fed ancient volcanoes. (A, B, and C from Earth: Portrait of a Planet by Steve Marshak, 2001; modified from Lillie, 2005; D modified from USGS, 2005).
Visitors may have a difficult time visualizing the relationship between volcanoes on Earth’s surface and the plutons beneath. One way to help them is to build on the Oreo Cookie® demonstration of a subduction zone (Figure 2.4b) using state quarters (Figure 2.9). Magma is generated at a subduction zone. As it rises toward the surface of the Earth it pools within chambers deep beneath the surface that feed volcanoes, such as Mt. Rainier depicted on the Washington State Quarter. If Mt. Rainier were to erupt so much material that most of its magma chamber were suddenly emptied, then it might collapse on itself and form a large crater, like the one holding Crater Lake and seen on the Oregon State Quarter. The Cascade volcanoes in Washington and Oregon are similar to what geologists think the Sierra used to look like. Magma beneath ancient Sierran Volcanoes cooled and crystallized very slowly forming large-grained, granite-type rocks. When subduction stopped volcanoes ceased to erupt. With continued uplift of the land, erosion removed most of the ancient volcanoes and the plutons that made up their chambers were exposed at the surface. The first rocks to be exposed were similar to rocks seen at Crater Lake. Both volcanic and plutonic rocks are exposed at Crater Lake. Over time, enough rock was removed and the rocks that make up Yosemite’s landforms today, such as Half Dome on the California State Quarter were exposed.

There are three sets of regional joints in Yosemite. Two nearly vertical joint sets are perpendicular to each other, one set trending northeast and the other trending northwest. Where the third, horizontal joint set, intersects the two vertical joint sets the bedrock forms large rectangular blocks like those found at Clouds Rest. A fourth notable joint set slopes about 45º westward.

Regional-scale joints are responsible for features such as the flat face of Half Dome, notches such as Gunsight, the near-vertical face of Sentinel Rock, the shear cliff below Glacier Point, and possibly the orientation of relatively straight, narrow canyons like Tenaya Canyon and Little Yosemite Valley. Inclined joint sets also influence many of Yosemite Valley's famous landforms. The angled faces of Three Brothers follow a set of inclined master joints that slope about 45º westward. A similar slope between Cathedral Rocks and Bridalveil Creek also follows a set of inclined joints (Figure 2.10).

Dense, unjointed rocks (especially those rich in silica, like granite) cannot easily accommodate changes in stress patterns. Yosemite’s granite-type rocks were formed as plutons deep underground where the weight of the overlying rock compressed the underlying plutons. Over time the overlying rock eroded away, gradually releasing the pressure. As a result the dense granite-type rocks expanded and developed curved cracks parallel to the surface topography, called sheet joints or exfoliation joints (Figures 2.11 and 2.12) producing a rounded
Figure 2.10. (A) Rectangular blocks, similar to cinder blocks, form where horizontal and vertical joints intersect. These rectangular blocks are near Glacier Point, but similar blocks are found throughout the park. (B) Vertical joint sets also dictate features like the flat face of Half Dome and orientation of Cloud’s Rest and Tenaya Canyon. (C) The Cathedral Rocks owe their characteristic triangular peaks to a set of joints inclined about 45° to the horizontal. (Photos by Sarah Dunham).

surface. Generally accepted hypotheses suggest that if the granite underlies a hill, the sheeting will produce a dome, for example North Dome; if the granite underlies a valley, the sheet joints will produce a bowl-shaped basin, for example Tenaya Canyon. Sheet joints can also form on vertical surfaces like cliff walls, for example, the Royal Arches.

Some rock types, like the Half Dome granodiorite, characteristically develop sheet joints. It forms nearly all the domes in Yosemite Valley including Half Dome, North Dome and Liberty Cap. Sentinel Dome is also the result of sheet jointing but is composed of El Capitan Granite.

Zoom In: The Low Down on Uplift

Around the same time as the Basin and Range Province was rifting (extending), the Sierra Nevada rose and tilted westward, forming an

Figure 2.11. Nature hates a sharp edge! When overlying material is eroded and removed from the top of the confined granite-type rocks, the rocks re-distribute internal forces and crack along curved joints. Arc-shaped layers form and fall off, like an onion. Over time, even the roughest edges are smoothed to form the dome-like structures famous in Yosemite.

Figure 2.12. Sheet joints are responsible for the onion-like layers along the Tioga Road, Yosemite’s characteristic domes, and many of the arches in the park. (Photo by Sarah Dunham).
A New perspective on Sheet Joints

Science can be described as levels of doubt; when someone presents a hypothesis the other scientists will be skeptical at first. As evidence is collected and analyzed, other scientists become less skeptical if the new evidence seems to support the hypothesis, or the hypothesis may be abandoned if the evidence appears to contradict it. Steve Martel is currently re-investigating existing explanations for the formation of sheet joints. He argues that tensile forces (pulling forces) at right angles to surface topography (not the release of confining pressure) are required for large sheet joints to form.

Where does the tension come from (Figure 2.13)? Two opposing forces are always at work on a body of rock. There is an inward and downward force produced by the weight of the rock and a compressive force pushing inward and upward against the weight of the rock. When the upward force is greater than the downward force, the rock "feels" tension at the surface and sheet joints form.

There are still many aspects of sheet joints that are not completely understood including the interaction between sheet joints and regional-scale shapes of sheet joints. These questions can likely be answered following detailed mapping on sheet joints and their surrounding topography.

Asymmetrical mountain range with a steep eastern slope (Figure 2.14). The more gradual western slope, where much of Yosemite lies, extends beneath California’s Central Valley where it has been covered with sediment from the eroding Sierra Nevada. Visitors who come into Yosemite via Hwy 120 over Tioga Pass, the steep east side, and exit via one of the other roads along the more gradual west side, experience these characteristics of the region firsthand.

The Sierra Nevada are part of the buoyant continental crust that “floats” on the underlying, denser mantle. The mountains represent an enormous weight of rock pushing down. This immense downward force displaces some of the underlying mantle. But if the crust is thick, an upward force from the crustal root below the surface balances the downward force of the mountains on Earth’s surface. When the downward gravitational forces balance the upward buoyant forces, an equilibrium is established (Figure 2.15). Geologists describe this state of balance with the word **isostasy**. **Isostatic equilibrium** is similar to lying face down on a beach ball in a swimming pool. The buoyancy of the beach ball lifts just enough of your body out of the water to weight down the ball. When you stop bobbing up and down, you and the ball are in isostatic equilibrium - you don’t move up or down.

Because the Sierra Nevada is a tall mountain range it might be expected to have a thick, buoyant crustal root supporting its weight (Figure 2.15A). But seismic studies that imaged the underside of the Sierra Nevada show that the crust is not significantly thicker than crust in surrounding, low-lying regions, suggesting that the weight of the topography is instead supported by hot, buoyant asthenosphere (Figure 2.15B).

It is likely that a thick crustal root supported the Sierran volcanoes as compressive forces and magmatism thickened the crust (Figure 2.15A). As the crust thickened the lower portions of the lithosphere were exposed to higher temperatures and pressures, causing dense minerals to form. Eventually enough dense minerals crystallized that the mantle lithosphere (the lithosphere underlying the crustal root) was denser than the underlying asthenosphere and was removed. Current explanations suggest the dense mantle lithosphere dripped or peeled off (delaminated) because it was denser than the underlying mantle. Removal of part of the deep lithospheric slab would allow hot, buoyant material to rise up under the mountains, which would support the tall peaks (Figure 2.15B). The hot, buoyant material might have been buoyant enough to cause the Sierran peaks to rise.
Figure 2.14. Cenozoic tilting during rifting in the Basin and Range Province formed the asymmetrical Sierra Nevada Mountain Range. To the east lie ancient ocean sediments and continental rift deposits in the Basin and Range Province. Gentle western slopes channeled much of the material eroded from the high Sierran volcanoes. One could say the ancient Sierran volcanoes are now upside-down in California’s Central Valley – eroded particles from the upper (younger) portions of the volcanoes are now sedimentary layers at the bottom of the valley, while the lower (older) portions are now on top! Erosion of overlying volcanic material exposed the underlying plutons that make up the Sierra Nevada Batholith. These intrusive igneous rocks represent the magma chambers that once fed volcanoes in the Sierra.

A) Middle- to Late-Mesozoic (about 200 to 80 million years ago)

B) Middle Cenozoic (about 35 to 10 million years ago)

C) Late Cenozoic (about 5 million years ago - present)
When did the mountains rise? Researchers have used several methods to decipher the history but different methods suggest different things. Recent studies suggest that there was a period of significant uplift (0.01 inches/year; 0.3 mm/year) from 3 to 1.5 million years ago that gradually slowed to the more modest rates seen today (0.0008 inches/year; 0.02 mm/year). How did scientists figure this out?

Questions regarding when and how fast the uplift occurred can be answered using evidence gathered from the volcanic deposits in the region. In isolated parts of the range between 20 and 5 million years ago volcanoes accompanying Basin and Range extension blanketed the landscape with ash and lava. Using radiometric dating geologists can calculate when minerals in ash and lava formed and thereby determine when the volcanoes erupted. At the time the volcanoes erupted, the ash and lava layers were flat deposits near sea level. We can thus date the layers and measure their present elevation, thereby estimating how fast the mountains rose.

Scientists are still debating the recent uplift history of the Sierra because the volcanic studies do not agree with other approximations. Yosemite is a key study area for this research, so stay tuned!

Figure 2.15. Isostasy illustrates the balance between the downward gravitational force (weight) of the topography overlying Earth’s crust and the buoyant upward force of material deeper within the Earth. (A) Downward gravitational force of the continental topography and upward buoyant force of the crustal root are in equilibrium. Notice that the topography has a relatively thick crustal root to support it. (B) Downward gravitational force of the continental topography and upward buoyant force of the asthenosphere. Notice that the crust has no significant root. Instead the weight of its topography is supported by the upward force of the hot, expanded mantle material (asthenosphere). Although (A) might have represented the situation when the Sierra were tall volcanoes like today’s Andes Mountains, the current situation is more closely represented by (B). (C) One analogy for helping visitors to connect to the meaning of isostasy is to have them imagine floating on top of a beach ball in a swimming pool. Their weight will push the ball under the water but the buoyant force from the ball (equivalent to a crustal root or hot expanding asthenosphere) will push up until just enough of their body will be out of the water to balance the upward force of the ball. (Modified from Lillie, 2005)
Geologic Time: Countdown to a Birthday!

Geological time is a hard concept for visitors to grasp because our lifetime is an extremely tiny fraction of geological time. Yosemite has been a work in progress for about 245 million years. That’s a long time! Well, compared to the age of planet Earth (4.54 billion years = 4,540 million years), maybe that isn’t so long. 245 million years is only 1/18 of Earth’s lifetime.

Using a human lifetime is a good way to illustrate just how young Yosemite is and convey the age of certain features. My grandmother (Grandma Goose) just turned 80, so I like to use her lifetime as a parallel. If Yosemite was also turning 80 and Earth’s birth date of 4,540 million years ago corresponds to Goosie’s birth date, then the granite-type rocks started to form when she was 76 (~245 million years ago), the granite-type rocks cooled when she was 78-79 (~116-85 million years ago), the granite-type rocks were first exposed at the surface about a year (65 million years) before her 80th birthday, the mountains started to uplift between 8 and 2 months before her 80th birthday, glaciers began to form in Yosemite between 8 and 2 hours (about 800,000-20,000 years) before her 80th birthday, and people first occupied Yosemite Valley 55 minutes (6,000 years) before her 80th birthday bash.

Remember: Some visitors do believe that the Earth is only a few thousand years old. Visitors have the right to retain and express their own beliefs and values. It is not your job to convince them otherwise. It is your job to present accurate and balanced scientific information. Using a metaphor, such as Goosie’s birthday, the length of a day or the length of a year can help visitors appreciate deep time, whether they consider a long time to be a few thousand years or a few billion years.
Chapter 3

Changing Climate Sculpts Unique Landforms

“The Yosemite Problem”

Yosemite Valley is famous for its dramatic display of sheer cliffs, cascading waterfalls, and flat meadows where the Merced River meanders through (Fig. 3.1A). Visitors are often curious about how such a singular landscape formed. Efforts to understand the origin of Yosemite Valley can be traced to at least the 1860’s. Josiah D. Whitney of the California Geological Survey championed the idea that the steep walls and flat bottom of Yosemite Valley were the result of the bottom dropping out; the two steep sides were fault planes and the flat bottom the rigid block that dropped out (Figure 3.1B). John Muir advocated the role of glaciers in the formation of Yosemite Valley (Figure 3.1C). In the 1870’s these two opposing viewpoints became the center of a sometimes-bitter dispute referred to as the “Yosemite Problem” or the “Yosemite Controversy”. In 1913 the U.S. Geological Survey, at the request of the Sierra Club, assigned Francois Matthes the task of determining the valley’s origin. His interpretation focused on the relative influence of glacial erosion during cold climates and erosion by the river in warm climates. When it was published in 1930, his interpretation of Yosemite as a glacially-scoured valley partially filled with sediment (Figure 3.10) was well received and ended the dispute.

Figure 3.1. Yosemite Valley has steep sides and a flat bottom (A). A valley formed by a down-dropped fault block looks a lot like Yosemite Valley: it has a flat bottom and steep sides (B). A glacially-carved valley is generally a U-shape (C). A glacially-carved valley partially filled with sediment has a flat bottom and steep sides, similar to a down-dropped fault valley (D). The similarity of a down-dropped fault valley and a glacially-carved valley filled with sediment was the fuel for “the Yosemite Problem,” and is a classic example of how science works.
Changing Climate, the Scenery-Sculptor

Landforms are unique but the processes that sculpted them are not. There is an inherent link between the nature of the bedrock, the climate it experiences, and the physical processes associated with that climate. Yosemite’s granite-type rocks have been exposed to cold and warm climates since they were uncovered at Earth’s surface. These climates have distinctive influences on the character of the landforms we see today.

Milankovitch Cycles

Earth receives about the same amount of energy from the sun every year. So how can climate vary so drastically at a given place on Earth? It turns out that it is not how much, but where and when Earth receives the energy from the sun that is most important. Milutin Milankovitch (a Yugoslavian astronomer) proposed in 1930 that the angle of incoming solar radiation (insolation) received at 65° N provides critical insight into the cyclic nature of ice ages. Think of the sun as a flashlight and the Earth as your head (Figure 3.2). If the insolation angle is straight on, then the sun is like a flashlight shone straight in your eyes. A lot of direct energy concentrated in your eyes makes it hard for you to see because your whole eye is receiving direct light. Similarly, when the insolation is “straight on” glaciers would likely be shrinking because the direct energy from the sun is received by more of Earth’s surface. If the light were angled, like when you turn your head up or down to avoid the direct light, then only diffuse energy reaches your eyes and you can see. Similarly, when the path of insolation is angled a large portion of Earth’s surface is receiving diffuse rays so there would likely be larger glaciers.

How do you change the angle of insolation? Milankovitch identified three cycles that change the amount and angle of insolation: eccentricity, tilt, and precession (Figure 3.3). Eccentricity changes the shape of Earth’s orbit around the sun. High eccentricity means the orbit is more of an oval; low eccentricity means the orbit is more circular (3.3A). An oval orbit means sunlight generally has to travel farther to reach Earth so less energy reaches Earth. Tilt is the angle the Earth’s rotational (north-south) axis makes with a line that is vertical relative to the plane of Earth’s orbit around the sun (3.3B). If the Earth’s rotational axis is tilted a lot then during summer or winter it receives direct sun rays over part of one hemisphere and only indirect rays in the other. At a fixed latitude, the insolation changes during the winter, spring, summer, fall cycle, even though the total insolation received by the planet stays the same. If the Earth’s axis is not tilted, then at a given latitude it receives the same amount of insolation all year round and there are no seasons. According to Milankovitch, high tilt favors large glaciers while low tilt favors small glaciers. Precession is the “wobble” of Earth’s axis. (Think of a top as it loses momentum and its axis begins to move in circles.) Precession changes the timing of summer and winter (3.3C).

Summer in the northern hemisphere happens when the axis is tilted toward the sun (receiving more direct insolation); winter happens when the Earth is tilted away from the sun (receiving more indirect insolation).
Figure 3.3. A) Low eccentricity means Earth’s orbit is more circular. High eccentricity is more elliptical and favors growth of glaciers. B) Low tilt angles (21.5°) mean there is a smaller change in climate from the equator to the poles. High tilt (24.5°) favors glaciation because there is a large change in climate from the equator to the poles: more of the Earth is cold and can sustain glaciers. C) Summer occurs when Earth’s axis is tilted toward the sun, winter when it is tilted away. Glaciation is favored when Earth is farther away from the sun in the northern hemisphere’s summer than in winter. D) These effects add and subtract from one another to produce warm and cold cycles of Earth’s overall climate that can be measured in various ways. $\delta ^{18}O$ refers to the ratio of Oxygen isotopes ($O^{18}$ compared to $O^{16}$) in polar ice. Note that high $\delta ^{18}O$ coincides with warmer overall climate; low $\delta ^{18}O$ coincides with cooler overall climate.
tilted away from the sun (receiving diffuse insol-
ation).

Eccentricity, tilt, and precession work together to change the intensity of sunlight during the summer months and initiate the growth of glaciers. (Summer is the crucial season for glacial growth; winter will always be cold, but if summer is cold too, then glaciers are likely to grow.) Eccentricity is able to amplify or subdue the combined effects of precession and tilt, however eccentricity’s effect on glaciation is small when compared with the effect of precession and tilt. Small glaciers are favored when the tilt is high (the poles receive more direct sunlight during the summer) and the eccentricity and precession are such that summer occurs closest to the sun. Large glaciers are favored when the tilt is low (the poles are receiving only diffuse sunlight in all seasons) and the eccentricity is high (Earth’s orbit is more elliptical).

The details of eccentricity, tilt, and precession might be hard for visitors to follow. If you would like to work this into a program try acting out the graphics in Figure 3.3 using your hat as the Earth and a visitor as the sun (hold the hat with the brim pointing upward to represent Earth’s axis at the North Pole). This strategy shows the geometry of the different cycles and keeps everyone involved.

Growing Glaciers and Gouging Granite

Imagine what would happen if summers began to get cooler. First, summer would feel like fall and eventually it would feel like winter all year because the snow that fell in winter would still be there in the summer. If this were to happen, the snow would collect layer upon layer upon layer. As the weight of the overlying snow increased, the underlying snow would compress and compact under the increasing weight of overlying snow, forming firn where there are still connected air bubbles in the ice. As the weight of the overlying snow continued to increase, the snow would compact into glacial ice, where there are only isolated bubbles of air within the ice. Eventually enough weight would be added so that ice would begin to flow downhill under its own weight, forming a glacier.

Glaciers grow larger when more snow falls in the winter than melts in the summer and smaller when more snow melts in the summer than falls in the winter.

When glaciers grow bigger they extend downslope from the ridgelines of mountains and flow into the low-lying valleys. Glaciers scrape along valley floors acting much like a bulldozer at the base. Erosion exploits existing weaknesses in the rock, such as joints. Substantial downward force from overlying ice can crack or enlarge existing cracks in bedrock. This process is called quarrying. How does quarrying work? As the ice flows high pressure and friction between the ice and bedrock may cause some melting. The flowing ice forces the melt-water into open spaces, such as cracks in the rock or air pockets behind obstacles. When enough water accumulates in these open spaces it can support some of the weight of the ice, lifting it off the bed. When these water-filled pockets drain quickly the pressure drops, the ice falls onto the bed, and the weight of the overlying ice is concentrated on the high points of the bedrock. The excess weight causes enlargement of existing cracks or new cracks to form in the bedrock. Draining a pocket quickly lowers the pressure, causing some of the liquid water to freeze around the

![Figure 3.4. Quarrying and plucking were active processes in the formation of many landforms in YNP. As the ice flows the friction and pressure of the ice on a bedrock knob begins to melt some of the ice. Pressure from the flowing ice forces water into open spaces, such as cracks in the rock or air pockets behind obstacles. A cavity full of water will support some of the weight of the ice. When a cavity drains quickly the weight of the floating ice is concentrated on high points in the bedrock enlarging existing cracks or forming new cracks. Release of pressure in the cavity causes the water inside the cracks to freeze so loose rocks are incorporated into the flowing ice. Eventually large rock fragments (up to several feet wide) are pulled loose from the bedrock.](image-url)
the newly formed blocks. Loosened fragments of rock are then incorporated into the flowing ice. This process is called plucking (Figure 3.4).

Once rocks are frozen into the ice they are called tools; literally, they are hard implements that wear away the bedrock. Some of the smallest-scale quarrying features are striations and arc-shaped gouges in the bedrock where tiny flakes of rock were removed. Striations are small scratches or furrows in bedrock formed when rocks frozen in the ice scrape along the bedrock chiseling out a clean line. The horns of the arc-shaped gouges may point up-ice (crescentic gouges) or down-ice (lunate gouges). When arc-shaped gouges appear in succession, they are called chatter marks. The gouges indicate what direction the ice was moving; run your hand over the gouge; the steep side is the down-ice side (Figure 3.5). Geologists can use striations, chatter marks, and lunate gouges to reconstruct what direction the ice was flowing.

The smaller rock grains frozen into a glacier can act like sandpaper and smooth the bedrock. This process is called abrasion and the results can be seen in glacial polish that glistens in the sun.

Abrasion can also happen on a larger scale during pothole formation. Potholes are depressions formed where sediment-laden streams of water swirled in a circular fashion and eroded a smooth depression. In streams beneath glaciers the swirling action can be driven by the stream flowing through an existing low point or by the downward force of a glacial waterfall, called a moulin. The force of the water on the bedrock erodes a low point where rocks are trapped in a swirling motion. As the rocks knock against the sides of the pothole it gets bigger. Some easily-accessible, glacially-related potholes are found on Pothole Dome in Tuolumne Meadows (Figure 3.6). Potholes may

*How do you know which way the ice flowed?*

![Diagram](image)

*Figure 3.5.* a) Striations are long, thin scars in bedrock where rock and sediment debris frozen into the base of a glacier scraped across the underlying bedrock. They indicate the orientation of ice flow but not the direction. b) Crescentic gouges are formed when large rocks frozen into the glacier are pushed down on bedrock, creating a conical fracture. The steep side of the gouge indicates the direction ice was flowing from. c) Chatter marks form when debris frozen into the base of the glacier is dragged along the underlying bedrock and catches repeatedly. The gentle side of the fracture indicates the direction the ice was flowing from. Having visitors run their hand over the arcuate fractures helps them feel what direction the ice was flowing.
also form by non-glacial processes. They commonly develop near the top of a waterfall where rocks have been trapped in the rapidly flowing water.

**Cirques** are amphitheater-shaped basins that form at the head of a glacier via large-scale erosion (Figure 3.7). As the glacier grows its erosive power increases. Over time, the glacier carves a small hollow that grows into the familiar bowl-shape. Cirques are typically surrounded on three sides by steep cliffs; the highest cliff is often called the headwall, the two lower side cliffs are called flanking walls. The fourth side is a low point that represents the side the glacier flowed out of and is called the “lip”.

**Rouche moutinée**, French for “rock sheep,” are asymmetrical humps of bedrock with an abraded, shallow-angled side and a quarried, steep-angled side (Figure 3.8). The smooth shallow side indicates where the ice was flowing from. Small particles at the base of the flowing ice scoured the surface smooth. At the peak of the hump large-scale processes like quarrying and plucking dominate to form the rugged, steep down-ice side.

As glaciers grow, they become increasingly confined by low-lying topography such as V-shaped river valleys. A river of ice differs from a river of water because ice is less fluid than water and flows more slowly. The mass of ice spreads over more of the valley, so the valley gets wider as well as deeper. As a glacier flows down a valley, it is most effective at eroding near the center because the ice is flowing fastest there. The glacier smooths out the V-shaped slot produced by the concentrated cutting from the river in the center of the valley, resulting in the familiar U-shaped glacial valley with steep sides and a smooth bottom (Figure 3.9). U-shaped glacial valleys are visible in many places in the park. Some of the most accessible are Yosemite Valley, the top of Upper Yosemite Falls, and Tenaya Canyon.

Hanging valleys are small tributary valleys that were occupied by smaller glaciers that could not erode as effectively as the main valley glacier because they were flowing more slowly. Because of the difference in erosive power the smaller U-shaped valleys appear to be hanging high above the main stem of the valley. Waterfalls mark many hanging valleys in Yosemite, for example Yosemite Falls emerges into Yosemite Valley from a hanging valley.

**How Big Were Yosemite’s Glaciers?**

Yosemite’s glaciers originated at the high peaks of the Sierra and extended over 15 miles from their source. How do we know this? Glaciers act like conveyer belts, transporting sediment from their source toward their down-slope boundaries, forming **moraines** (Figure 3.11). The moraine that forms when a glacier is at its longest extent is called the **terminal moraine**. As the glacier shrinks and forms successive moraines at its farthest extent, those piles of debris are called **recessional moraines**. Moraines formed on the sides of a glacier are called **lateral moraines**, and the moraines that form between two converging glaciers are called **medial moraines**. All of these features help geologists to decipher when glaciers occupied various parts of Yosemite and what effects they had on the landscape.

In the lower elevations of Yosemite, terminal moraines show evidence for three stages of glacia-
tion: the Sherwin Stage (800,000-860,000 years ago), the Tahoe Stage (49,000 years ago), and the Tioga Stage (17,000 years ago). In the high country, there is evidence for two more recent glaciations, the Recess Peak and Matthes Stages (13,200 years ago and 700 years ago). Glaciers act like bulldozers, scraping the granite landscape clean as they advance. If a glacier occupied Yosemite and then was followed by a more-extensive glacier, the record of the first may be completely erased. Many additional glaciers may have occupied the Yosemite region, but there is no evidence for them, or no one has identified them yet.

Moraines are found throughout Yosemite National Park. The “Terminal Moraine” of the Yosemite Glacier is located near the Bridalveil Fall vista on Southside Drive. It looks like a small hill on either side of the road where the turnout lanes end and includes a large, conspicuous chunk of Cathedral Peak Granodiorite. Another easy-to-spot moraine is the “El Capitan Recessional Moraine.” This moraine looks like a small hill on the left as you leave El Capitan Meadow. The “Medial Moraine” is a small hill across from the Delaware North Company stables in Yosemite Valley. The names of these moraines are in quotes because they make assumptions about the nature of the moraines. “Terminal Moraine” suggests the moraine near Bridalveil Fall was the farthest the ice extended at the time, and “Medial Moraine” would mean that this moraine marks the juncture of glaciers that occupied Little Yosemite Valley and Tenaya Canyon. These interpretations are not necessarily accurate.

Figure 3.7. Cirques are easily identified by their steep headwalls, flanking walls, and bowl-shaped amphitheater. They are concentrated near the ridge lines in the High Sierra. Geologists study cirque dimensions (length vs. width; length vs. depth) to determine how active the ice was and how long ice occupied a given cirque.

Figure 3.8. Lembert Dome is a rouche moutinée-shaped landform. The summit of Lembert Dome is a popular destination for visitors to Tuolumne Meadows. The trail takes about half a day and loops all the way around the base with a short jaunt up to the summit. The hike up to the summit follows the shallow up-ice side of the dome. From there, visitors can get a panoramic view of the meadows and look closely at some polished granite-type rocks while they eat lunch.
When engaging visitors in the formation of Yosemite Valley, glacial erosion will undoubtedly come up. Ranger Andy Fristensky uses the “Yosemite handshake” to demonstrate the effects of glacial erosion on a V-shaped river valley.

To execute the “Yosemite Handshake” have visitors pair up. One visitor will make a narrow V with their hands to represent a V-shaped river valley and the second visitor will make a fist to represent a glacier. Have the visitor who made a fist push their fist into the steep V mimicking the advance of a glacier into a river valley. The fist “erodes” the valley into a characteristic U-shaped glacial valley (Figure 3.10).

Glaciers also leave behind trimlines. A trimline is a boundary line on a glacier-confining feature that shows the maximum height of glacial ice. In Yosemite, trimlines are easily identified by a change in color or weathering state of bedrock (Figure 3.12). Ice in the Sherwin stage of glaciation filled Yosemite Valley almost to the top while ice in the Tahoe and Tioga Stages did not. Rocks at the top of the valley that were exposed during the Tahoe and Tioga Stages are more weathered – they
appear darker and more vegetated. For example, the steep face at the top of El Capitan that climbers scale was glaciated, but the top where the slope is more gradual was not covered by ice.

**Yosemite’s Living Glaciers**

There are currently two glaciers in Yosemite National Park: Lyell Glacier on Mt. Lyell and Maclure Glacier on Mt. Maclure. Yosemite’s “living glaciers,” as John Muir called them, are rapidly shrinking. Both of Yosemite’s living glaciers are on the north-facing slope of the peaks they occupy. North-facing slopes receive less energy from the sun so glaciers on these slopes commonly are the last to melt. One way to help visitors visualize shrinking glaciers is to look at pictures of glaciers taken early in the 20th century and compare them with modern-day pictures (Figure 3.13). Recent photos can also be used to illustrate details of glacial geology because the moraines are well developed and the cirques and small alpine valleys are still crisp and easy to identify.

**What Happens After the Glaciers Retreat?**

As glaciers expose bare granite to the elements, the rock begins to weather and becomes susceptible to erosion. Erosion describes local movement of rock particles, while transportation is the long-distance movement of particles from a rock’s origin. After rocks are eroded and transported they are deposited where they come to rest. Some examples of deposits in Yosemite are glacial moraines, beach sands along rivers, and talus piles. Over time some sedimentary deposits are buried and compacted, and may eventually become sedimentary rock. Geologists use the word diagenesis to describe all the changes a deposit undergoes as it is buried. Diagenesis encompasses processes such as compaction, cementation of particles into a mass, and lithification of particles into a sedimentary rock (Figure 3.14).
Figure 3.13. A) Lyell Glacier in 1934. The glacier extended all the way to its terminal moraine, the dark feature (rock debris) beginning to emerge from the white at the maximum ice extent. B) Lyell Glacier in 2004. Since 1934, the glacier has retreated toward its headwall, leaving the terminal moraine totally exposed. Notice that the glacier no longer wraps around the boulder at the left of the terminal moraine.

There are two major kinds of weathering. Chemical weathering is the process by which rock material is altered, dissolved, or oxidized (rusted) into a second product that is stable near Earth’s surface. Mechanical weathering is the process by which rock material is physically broken into smaller pieces by processes such as ice formation, expansion or contraction due to temperature change, exfoliation, and wedging by plant roots.

Chemical weathering is an important first step in the breakdown of solid rock. When it rains, the water (H₂O) activates several processes (Figure 3.15). Hydrolysis is a reaction between the minerals in the rock and the hydrogen in the rainwater to produce a new, less resistant mineral or decompose an existing one. A common example in Yosemite occurs when feldspar weathers to produce clay due to exposure to air and water. The clay appears on weathered feldspar crystals as a fine, light-colored (gray or white) layer that you can brush off with your hand.

Another chemical weathering process involving the interaction of minerals with water is hydration that occurs when a mineral crystal absorbs water and expands like a sponge. Remember biotite? It’s put together in sheets. Those sheets soak up the water and expand. Eventually the mineral crystals expand so much that they fall out, allowing the water to penetrate deeper into the rock. Hydrolysis and hydration are especially important in the formation of grus, a fine-grained granite sand.

First, feldspars weather to clay via hydrolysis. Next, the sheets of clay minerals and biotite hydrate as they are exposed to water. As they expand and fall out the rock disintegrates into a slippery grus that blankets many of Yosemite’s trails. Why is grus so slippery? Small mineral crystals that are resistant to weathering (for example, quartz), act like ball bearings; they reduce friction between your foot and the trail so that you tend to slip. This is the stuff that can lead to bloody knees and sprained ankles!

A third chemical weathering reaction called oxidation forms the brown streaks on the cliffs. (The black to gray streaks are lichen, which are living organisms). During oxidation elements in minerals react with the oxygen in the air and form new minerals. The brown streaks are iron oxide (rust), where the iron in minerals such as biotite and hornblende combine with the oxygen to form iron oxide. Why does it form streaks? The iron oxide crust crumbles easily and can be spread out by rainwater. As the rain drips down the cliff faces, it stains the rocks (Figure 3.16).

Because chemical weathering largely requires water to be present and un-fractured granite-type rock is not very permeable to the flow of water, Yosemite’s cliffs weather VERY SLOWLY! The weathering in unfractured rock tends to concentrate around the mineral grain boundaries because that is where the greatest weaknesses are. This process is difficult to see because the minerals are usually small. However, the Cathedral Peak Granodiorite (readily visible on the trail from Cathedral Lake to Sunrise) has HUGE rectangular feldspar crystals, and these stick out in relief in weathered rocks.
Figure 3.14. Bare rock surfaces are exposed to air, wind, water, and ice. Over time dense, strong rocks are weathered to more easily-eroded material, then transported and deposited as sedimentary particles away from their source. Over time the new sediment layers are buried and compacted by the weight of more sediment. The term “diagenesis” describes the processes that turn the compacted sedimentary particles into hard sedimentary rock.

Hydrolysis: Water interacts with the minerals in the rock producing new minerals.

\[
2 \text{KAlK}_3\text{O}_8 + 2\text{H}^+ + 9\text{H}_2\text{O} \rightarrow \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 + 4\text{H}_4\text{SiO}_4 + 2\text{K}^2+ \\
\text{Potassium feldspar} \quad \text{Hydrogen ions} \quad \text{Kaolinite clay} \quad \text{Silicic acid} \quad \text{Potassium ions}
\]

(from water) (dissolved in liquid) (dissolved in liquid)

Hydration: Water alters the structure of minerals but no new minerals are produced.

\[
\text{KFe}_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2 + \text{H}_2\text{O} \rightarrow \text{KFe}_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2 + \text{H}_2\text{O} \\
\text{Biotite Mica} \quad \text{Water} \quad \text{“Bloated” Biotite puffs-up with water.}
\]

Figure 3.15. Water interacts with rock and decomposes it via hydrolysis and hydration. During hydrolysis, water interacts with the minerals in the rock to produce new minerals. This is a common reaction, for example, where feldspars weather to clay minerals, such as kaolinite. When a mineral undergoes hydration, water is incorporated into the structure of the mineral, expanding the mineral. The expanding mineral pushes all the neighboring minerals apart and the rock crumbles.
Mechanical weathering is also important because it physically breaks rock into smaller sedimentary particles. There are several processes in Yosemite that are examples of mechanical weathering. Abrasion occurs when small fragments are broken off large rocks by wind and/or water and are worn down as they crash into different obstacles. Rivers are good places to look for evidence of abrasion. Rocks carried in the flow of rivers are smooth because they have crashed into other rocks and the river-bed along the way, dulling their sharp edges. Sometimes these rocks get stuck in a swirling motion on one spot and erode a pothole (Figure 3.8). Potholes are common at the precipices of waterfalls and fast-moving portions of the main stem of a river.

Temperature also has a marked effect on mechanical weathering of large exposed surfaces. During the day, rocks are exposed to sunlight and warm up and expand. At night, rocks cool and contract. Expanding and contracting every day weakens the rock and the rocks respond by forming curved cracks almost parallel to the surface (similar to sheet joints). Curved cracks parallel to the surface of the rock produce curved slabs that may fall off at any time (Figures 2.11, 2.12, and 5.5)!

**Frost wedging** (or ice wedges as my brother calls them) utilizes the joints, cracks, and divots produced by abrasion and exfoliation (Figure 3.17). Water percolates down into the cracks in the cliffs and crevasses of rocks. When the temperature is cold enough the water freezes and expands forming ice. Because ice takes up more space than water, ice formation increases the stress in the rock. When the stress is high enough the crack en-

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**Figure 3.16.** Visitors often notice the streaks of oxidation on the cliffs. Oxidation streaks can be a good talking point because they relate to seasonal cycles. Paths of seasonal (ephemeral) waterfalls are often marked by oxidation streaks. (Photo by Sarah Dunham.)

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**Figure 3.17.** Joints are the weaknesses in dense, strong granite rocks. A) Water enters joints in the rock. B) In the late fall, winter, and early spring the temperature drops below freezing and the water freezes, causing an increase in stress in the crack forcing the crack to widen. C) When the ice melts, rock particles inside the crack are dislodged and water seeps farther down into the enlarged crack.
larges to accommodate the ice. As the ice thaws, water percolates farther down onto the crack in the rock. Eventually, frost wedging forces the crack to propagate through the rock and the free-standing fragment breaks off.

Organic activity has a similar effect as frost wedging. Plants grow in soil that collects in the cracks. As the plants grow larger, their roots also get larger and push the sides of the crack farther and farther apart, allowing water to percolate farther down into the rock. Once these rocks are sufficiently separated from the wall, they fall to the floor below.

Rock type also plays a role in weathering (Figure 3.18). Silica-rich rocks (granite; granodiorite) are typically more sparsely jointed than silica-poor rocks (diorite; gabbro). Why? When plutonic rocks cool and solidify they decrease in volume and develop micro-cracks. Silica-poor rocks experience a larger decrease in volume than silica-rich rocks, so silica-poor rocks develop considerably more micro-cracks than silica-rich rocks. When rock accommodates regional tectonic stress, such as extension in the Sierra Nevada Batholith during the Cretaceous, joints develop. Because silica-rich rocks have fewer micro-cracks than silica-poor rocks, they tend to have fewer large-scale joints. The more joints there are in the rock, the faster weathering occurs because water is in contact with more fresh faces.

How Does Climate Change Affect Yosemite National Park?

Some visitors are curious about the effects of climate change on Yosemite. At the end of the last major glaciation (about 12,000 years ago), bedrock in Yosemite was scoured clean of debris and soil. Since then the valleys have been filling themselves in via several processes. When glaciers melt, water often collects below the glacier’s terminal moraine forming a lake at the bottom of a cirque or a U-shaped valley. Ancient Lake Yosemite formed via this process and covered the floor of Yosemite Valley. Why aren’t visitors to Yosemite Valley treading water today? As the ice melted, eroded material frozen into the ice was deposited in flat layers, filling the lake. Geologists are unsure how many times Ancient Lake Yosemite existed and how big it was each time. Estimates suggest that the bedrock floor of Yosemite Valley lies about 2,000 ft. (600 m.) below Curry Village (Figure 3.19).

Yosemite’s glacially-scoured landscape was utilized in the construction of the Hetch Hetchy Reservoir that supplies a large portion of California residents with drinking water. The water level in Hetch Hetchy Reservoir, thus the amount of water Californians have to drink, depends on the amount of snow in the Sierra Nevada. About 75% of weather stations in the western US show a decrease in snowfall and an increase in rainfall over the past 50 years. What does this mean? If the trend continues, Californians may need to think about some significant lifestyle changes, or seek out a different source of water because Hetch Hetchy will no longer be able to support the growing population. Addressing this topic has the potential to foster some intellectual and emotional connections that may help people ponder more sustainable lifestyles. Changes in precipitation may also affect plant and animal distributions in the Sierra Nevada and may foster other connections. For example, groves of giant sequoia trees tend to be confined to the same drainage basin because there is more water available there than outside the basin. A steady supply of water year-round depends

Figure 3.18. The Diorite of the Rocksides has many silica-poor minerals such as biotite and hornblende, while the El Capitan granite has more silica-rich minerals. As one of the most silica-rich rocks in the park, the El Capitan Granite is one of the most sparsely-jointed. Conversely, the Diorite of the Rocksides is one of the most closely-jointed because it is silica-poor. Water can seep into the joints and accelerate weathering, resulting in a huge talus pile at its base. The El Capitan Granite hardly has any talus. (Photos by Sarah Dunham.)
on a large winter snow pack. Giant sequoia seedlings will only grow to maturity if there is enough water to sustain them in the early growth stages. If snow pack continues to decrease, we may lose the giant sequoia altogether.

Plant and wildlife species respond to warming trends by shifting their ranges to higher latitudes and altitudes – they literally run for the hills. One example of this phenomenon in Yosemite is the change in distribution of the pika. Pikas are fuzzy, potato-sized herbivores that inhabit the tops of Western US mountains like the Sierra Nevada. They have round bodies, obvious ears, no visible tail, and weigh in at a whopping 5 oz. (142 grams) (think of a small tomato paste can). Despite their cute appearance, they are one of the few mammals in the lower 48 states hardy enough to survive the whole year in the inhospitable conditions above treeline. During the late summer and fall months pikas are frantic workers; they collect large piles of wildflowers and grasses – a process called haying – to eat during winter. During the hot summer months, they descend into the cool moist talus piles at the base of mountains. Biologists fear the hardy pikas will not survive present global warming because they have nowhere else to go – they have run out of mountaintop.
Chapter 4

Living Among the Rocks: Yosemite’s Geology/Ecology Connections

Exposed bare rock faces might not seem like the most nurturing parent, but Yosemite’s granite-type rocks brought forth the diverse plant and animal communities seen in Yosemite today. These communities owe their existence to the advance and retreat of glaciers and the weathering, erosion, transportation and deposition of granite-type rocks on an asymmetrical mountain range.

Ranger Eric’s Hypothesis

There are two species of Hydromantes salamander in Yosemite: the Mount Lyell salamander and the Limestone salamander. Ranger Eric Westerlund has a hypothesis; he thinks these two salamander species originated from a common ancestor.

According to Ranger Eric’s hypothesis, about a million years ago, there was a single species of Hydromantes salamander living in Yosemite Valley. As the glaciers grew and advanced into Yosemite Valley, some of the single species of Hydromantes salamanders migrated up the valley walls while others migrated down valley into the foothills. Eventually ice filled the valleys so full there were only small islands of rock emerging from the top. Geologists call these ice islands nunataks. The ice separating the exposed granite nunataks from the foothills totally isolated the two groups of salamanders.

Salamanders living on nunataks evolved into the Mount Lyell salamander (4,000-12,000 ft.; 1,200-3,700 m). They have dark gray and brown speckles that look like granite from above. Their broad flat feet and short tail help them navigate the slick granite. Salamanders living in the foothills evolved into Limestone salamanders (1,200-2,500 ft.; 370-760 m). They are brown on top and pale on the bottom to blend in with the surrounding rocks (Figure 4.1).

![Figure 4.1](image_url)

*Figure 4.1. The Limestone salamander (left) and the Mount Lyell Salamander (right) are both of the same genus, Hydromantes, but they have adapted to life in very different environments. One of the most noticeable adaptations is their coloring. The Limestone salamander is usually a uniform reddish-brown mimicking the moist limestone crevasses that comprise its primary habitat, while the Mount Lyell salamander is gray with chocolate-brown speckles that form a granite-like pattern.*
**Rocky Residences**

As the glaciers melted, lakes formed within cirques and rivers flowed to lower elevations in the park. Initially there were no fish in lakes above 6,000 ft. (2,000 m.) because fish could not travel past the tall waterfalls that connect smaller tributaries to the main stems of the Tuolumne and Merced Rivers. As a result fishless ecosystems evolved in high alpine pools. There are amphibians and large insects found in these pools that are not found in streams where fish live.

When the glaciers retreated, they left erratics behind on high ground. Erratics are rocks that were frozen into glacial ice, carried as the ice flowed, and dropped to the ground as the ice melted. They are generally different from surrounding rocks in shape, size, and/or composition. Certain rock types are characteristic of different areas of the park and can be used to determine the routes of glacial ice flow. Today erratics are visible as solitary “sentinels” on the landscape and can be found almost anywhere in the park (Figure 4.2).

The underside of erratic rocks makes great habitat because it is wetter and cooler than the surrounding landscape. The underside of rocks also provides shelter from harsh conditions and a safe haven from predators. Many small animals, insects in particular, make their homes under rocks.

Some larger animals also make their homes under rocks in talus piles or talus caves. If you look closely at a talus pile, it is teeming with life, including invertebrate species new to science! Talus caves form when irregularly-shaped rocks fall on top of each other or into narrow fractures or canyons. The spaces are large enough that animals such as squirrels, mice, and bears often take shelter. Some talus caves have streams running beneath them part of the year. Water washes away small sediment particles leaving empty spaces around boulders that can serve as a spacious abode!

Life on the cliffs owes its existence to exposed joints in the steep, glacially-sculpted walls. Regional joints can extend several miles long and deep into the rock allowing large cracks to open into cave-like cracks and broad ledges. There are cracks on the cliffs that would swallow a small car and ledges where a tour bus could park. Large, protected spaces in these cracks and on ledges provide ample habitat for a variety of animals. It may seem like a precarious place to live, let alone raise a family, but there are some distinct advantages to living on the cliffs. Among them are a relatively predator-free environment and ample hiding places in case a predator does come hunting.

Rodents can happily live their whole life on the cliffs. They can forage for food and nesting

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**Sierra Yellow-Legged Frog**

Wildlife surveys from the early 20th century indicate that the Sierra Yellow-legged Frog was the most abundant amphibian in the Sierra Nevada at that time. The Sierra Yellow-legged Frog was among the top predators in these systems and served as an indicator for the health of the pools. A survey conducted in 2000-2002 suggests the population of Sierra Yellow-legged Frogs had declined by about 95%. The reason for this dramatic decline; in the mid-1800’s settlers, the California Fish Commission, the U.S. Army and other groups began stocking trout in the High Sierra to provide food and recreation for backcountry travelers.

Trout prey on the eggs and tadpoles of the Sierra Yellow-legged Frog. The trout may also have brought a disease with them; chytrid fungus. When a Sierra Yellow-legged frog is infected with chytrid fungus, it can no longer diffuse water into its system and waste out of its system properly and it dies. Chytrid fungus has killed many populations of frogs in Yosemite. YNP is now trying to restore the natural fishless conditions derived from glaciers to the lakes and streams in the Sierra Nevada and reintroduce the Sierra Yellow-legged Frog to these areas.

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*Figure 4.2. Erratic rocks, like this one at Olmstead Point, often provide shelter on exposed granite faces making them valuable hiding places for animals, including rodents and salamanders.*
material. Vegetation grows in soil formed by chemical and mechanical weathering that collects in the joints on the cliff. Several birds, such as the red-tailed hawk, the American kestrel, great horned owls, spotted owls, ravens, and peregrine falcons, also nest in protected corners of the cliffs. Birds can use the cliffs as a scouting place when hunting or take-off point when teaching chicks to fly.

Let the Flora Tell the Story for You!

Some of Yosemite’s hidden (and not so hidden) geology can be easily conveyed using plants as dynamic characters in a story. For example, take the California Black Oak in Yosemite Valley. It tends to grow on slopes or in valleys in well-drained, rocky soil near the valley walls; it doesn’t like to grow with its feet wet! Moving toward the center of the meadow the plants tend to shift more toward wildflowers and sedges. These plants thrive on the moist, organic-rich soils that develop along the floodplain of the stream running through the middle of the meadow. The soil in the meadows contains more clay, meaning it stays wetter longer than the well-drained, sandy, forested counterpart.

Giant sequoia groves also require a specific set of growing conditions. They are generally found in humid climates characterized by warm summers and snowy winters. They grow best in well-drained sandy soils derived from weathered granite. Full-grown giant sequoia are very thirsty trees so how do thirsty trees thrive in dry, well-drained soil? They cluster in wet places, near the bottom of drainages, at the edges of meadows, and near springs or seeps, where they can soak up the water directly from the source.

Some species will try to fool you. Lodgepole pines are some of the most robust trees in Yosemite. They grow in a variety of conditions including moist, cold drainages such as along streams and around meadows, but also thrive on steep slopes of well-drained glacial outwash where widely-spaced stands are subjected to intense winds. In some cases lodgepoles grow on floodplains where their seeds were deposited by floodwaters. Lodgepoles thrive in granite-derived soils so the meadows of Yosemite are a perfect place for them to take root.

Peregrine Falcons: Links to Life, Death, and Survival

Peregrine falcons are majestic birds of prey that may be seen nesting on the cliffs in Yosemite. There are nests on the North American wall of El Capitan and in the Royal Arches in Yosemite Valley, but the population was not always as healthy as it is today. DDT, a pesticide, was used in the 1950’s to 1960’s to enhance crop yields. At the time DDT seemed to be good for people because it meant we had a lot of fresh fruits and veggies to eat. However, it was bad for falcons and other birds because it caused the shells of their eggs to thin. Mother falcons incubating thin-shelled eggs would crush the eggs so her chicks would never hatch. Over time the population declined.

Rock climbers and researchers united to help save the falcons. On May 8, 1984, individuals from the Predatory Bird Research Group (of the Long Marine Lab in Santa Cruz, California) and volunteer climbers ascended to a peregrine falcon nest on the North American wall of El Capitan and removed the thin-shelled eggs from the nest. These eggs were destined for incubation by humans and introduction into a different nest. The next day, the climbers returned to the nest on the North American Wall and introduced two chicks hatched from eggs collected from another falcon. The mother falcon successfully raised these introduced chicks.

The efforts of climbers and the cessation of DDT use in the United States helped the peregrine falcon population rebound significantly all through the American West.
Chapter 5

Discovering “Your-semite”

When young children are asked “Are you ready to go to Yosemite?” more than you might think respond “Yeah, let’s go to My-semite!” This childhood misunderstanding is not only endearing, it is insightful. Each individual’s experience in Yosemite is unique, and these experiences are often deeply meaningful. Those who are captivated by the landscape respond to its cues unconsciously. People live on a landscape that was formed, and is continually modified, by geological processes. The reciprocal relationship between Yosemite’s landscape and its inhabitants is multi-faceted. This chapter introduces some connections between the geological landscape and the Yosemite Indians, sheepherders, miners, rock climbers, and present park visitors. As you read, think about the components of “Your-semite”.

The Ahwahneechee Utilized Geological Resources in “Their-semite”.

Archaeologists estimate that the first human occupation of Yosemite Valley occurred at least 4,000 years ago when the Paiute tribe crossed over the Sierra from the east to hunt and gather food. The Paiutes were joined later by the Sierra Miwok who spread into the Yosemite region from the west. As time went on, a sub-tribe of the Sierra Miwok established permanent villages along the Merced River. The tribes called this place “Ah-wah-nee”, probably from the Miwok word meaning “place of the gaping mouth”, and called themselves Ahwahneechee, people in the Ahwahnee.

The “gaping mouth” undoubtedly refers to the change in the character of Yosemite Valley as you come in from the west (from Mariposa). There is a noticeable shift from the enclosed feel of the steep-sided, V-shaped valley near Mariposa to the wider valley near El Portal, to the broad, flat-bottomed, and steep-sided Yosemite Valley. This change is due to the glacial erosion that resulted in Yosemite Valley’s characteristic U-shape. Moraines indicate that during the Sherwin stage of glaciation (750,000 years ago) ice extended all the way down to El Portal. Tahoe moraines (49,000 years ago) and Tioga moraines (23,000 years ago) suggest that later glaciers did not extend as far down-valley. The deepening and widening forces of glacial erosion were concentrated in Yosemite Valley, making it the widest, deepest part of the Merced River Canyon.

The Ahwahneechee and surrounding tribes depended on the meadows that formed after glaciation for sustenance. They hunted, fished, and gathered various edible plants, including acorns from oak trees (California Black Oak acorns were preferred). The Ahwahneechee used granitic mortars and pestles to pound acorns into flour so they could make acorn mush, bread, and acorn patties.

Pestles are small, hand-sized rocks handed down from grandmother to granddaughter. As granddaughters get stronger, they receive larger pestles and take on more of the pounding duties. A pestle is more than a hunk of rock. Each pestle has some of the acorn residue from the owner’s grand-

Geologic Intangibles are Woven into Sierra Miwok Legends.

The Legend of Tissiak is filled with intangible ideas that can be developed through interpretive programming. A long journey can be linked to hardship, challenge, and fatigue. The fight between Tissiak and her husband might engender respect, rage, anger, remorse, sadness, and pain. Geologic connections can be made as well. The domes open the door for a discussion of geological time, dome formation, and lichenometry. These tangibles can be linked to time and pressure. Tenaya Canyon opens the door to topics like rockfall, glaciation, and meadow formation, which can engender power, awe, and beauty.

The Legend of Tutokanula also contains many important tangibles. Tultakana’s journey can be tied to challenge, heroism, and determination. The cliff he climbed can be tied to some geologic tangibles including plutonism, glaciation, and rockfall. Some possible intangible connections to pursue could be safety and the incomprehensibility of deep geological time.
grandmother, from her grandmother, and her grandmother before that, all the way back to the very first grandmother. A pestle is a very special gift because it ties a person physically and spiritually with their family and the landscape.

Mortars also provided a special tie to place and family. They are local to an area (mostly because they are too large to move) and are often a place of reflection and learning. Solitary rocks are mortars that are removed from the center of the village and have only one pounding pit. These were used when someone needed time to be alone, either to reflect or to be angry. Binding rocks are mortars with two pounding pits and were often used when a grandmother, mother, or aunt was teaching a young girl about the finer points of pounding. These rocks strengthen the physical and spiritual connections between the grandmothers, granddaughters, and the landscape. Gossip rocks are central in the village and have multiple pounding pits. They were one of the gathering places for the women of the village and may have become the center of attention when there were stories to be shared!

Stories Communicate Meanings in the Landscape

People commonly remember compelling stories, not fragments of information. The Ahwahneechee used stories to educate, communicate accounts of important events, describe aspects of the landscape, and impart safety messages to members of their community. (In short, they were Yosemite’s original “interpretive rangers!”) Many of their stories incorporate geological information.

For example, the Legend of Tissiak opens the door for a discussion of exfoliation and dome formation. This legend suggests that Half Dome, North Dome, Basket Dome and Washington Column formed when Tissiak (Half Dome) and her husband Tecoya (North Dome) fought after a long journey into Yosemite Valley. After a shouting match, Tecoya threw his walking stick (Washington Column) at her and Tissiak threw her burden basket (Basket Dome) at him. For their wickedness to each other they were turned to stone. The Ahwahneechee also believe the dark streaks of lichen on Half Dome are Tissiak’s tears she shed during and after the fight (Figure 3.16).

The Legend of Tutokanula suggests that El Capitan was a rock by the river that rose while two bear cubs played and then fell asleep on top. The cubs slept for many seasons. The animal people missed the cubs and tried to rescue them from the top of the cliff. Tultakana, the measuring worm, was ultimately their rescuer. When Tultakana reached the top, he stretched across the valley and the walls started caving in forcing the animal people out of the valley. The caving in partly filled the valley and made up all the earth and piles of rocks that now make up the floor of the valley.

Meadows, Cliffs, and Rocks: Shepherds, Miners, and Tourists Discover Yosemite

Shepherds relied on the topography of the Sierra Nevada to nurture their flocks. In the winter months, they kept the sheep at low elevations in the Mariposa region. Come summer, and hot dry weather, the shepherds would drive their flocks up the gentle western slopes to the high country. The ultimate destination was the lush, string-of-pearl meadows that were formed as cirques filled with sediment when the glaciers retreated.

Why are the meadows in the high country so lush in the summertime? As the shepherds and

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Rocks: Links to Survival

The Ahwahneechee were unable to obtain everything they needed locally to sustain themselves in Yosemite Valley. They traded with the Mono Lake Paiutes to acquire obsidian for arrows, pumice for grinding, and salt, rabbit skins, and pine nuts. Regional geology helped archaeologists retrace trade routes. Obsidian and pumice are not naturally found in Yosemite Valley. They are extrusive rocks from recent volcanism during Basin and Range extension occurring on the eastern side of the Sierra. The salt comes from Mono Lake, one of the saltiest lakes in the world! Finding these things in Yosemite Valley suggests there was active trading between tribes on the east and west sides of the Sierra.

2 Legends can be a powerful tool in interpretive programs. But please use them with care. Many storytellers consider it theft when interpreters share stories as complete “legends” rather than “summaries.” An elder must gift a story to someone before they can tell it themselves. Make sure you are careful about how you share legends to respect the feelings of the traditional storytellers.
How do I Know if the Flake is Gold? Or is the Flake Fake?

Finding gold in the Yosemite region attracted thousands of miners. The successful miners were able to distinguish the real gold from the “fools gold.” Visitors often find things that look like gold in the rivers and streams in Yosemite, but it is unlikely that it is actually gold. There are several minerals that have a gold-like appearance including pyrite (the gold-colored, cube-shaped mineral commonly called “fool’s gold”), and yellow flakes of micas (such as biotite) that have weathered.

How do you know if your flake is gold? The easiest way to decide is to compare it to the imposters. If it looks like one of the imposters, it probably is. Another way to tell is to pan the unknown mineral like a miner would. Gold is heavy, so it will sink to the bottom of the sediment water slurry. Gold is also malleable (able to be pressed permanently out of shape without breaking or cracking), and ductile (able to be pulled into a wire). The imposters can’t do either of these things – they crack and break. Is your flake fake?
near the boundary of granite-type rocks and metamorphic rocks on the west side of the Sierra.

In 1857, word spread that rich silver deposits had been found on the east side of the Sierra in the “Sheepherder Vein.” The Great Sierra Mining Company and the Tioga mining district formed in response. The Tioga mining district included land from the foot of Bloody Canyon over the Sierran peaks and down the Tuolumne River to Soda Springs. But the miners never found the vein and abandoned these camps.

**Steep Slopes Challenge Road Builders**

Initially mines near the crest of the Sierra Nevada were only accessible from the east side. Supplies and equipment were packed up the eastern fault escarpment via the Bloody Canyon Trail. This was not an easy task. There were places where workers needed to “[hoist machinery] straight up…an almost vertical rise of 2,160 feet.” Winter snows made eastern trails practically impassable, prompting the Great Sierra Mining Company to construct the Tioga Road up the more-gently sloped (and less treacherous) western side of the mountains. The Tioga Road was completed in 1883 at a cost of $64,000.

Although the journey over the gently-sloping western side of the Sierra Nevada was easier than the steep fault escarpment on the eastern side, by no means was the journey easy. Miners and tour-

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**Figure 5.2.** A) A piton is a steel spike hammered into a crack or seam in the rock. It acts as an anchor to protect climbers against the consequences of a fall. B) A carabiner is a metal loop with a spring or screwed gate used to connect pieces of safety equipment. C) A cam or a “friend” consists of three or four teeth mounted on an axle. Pulling on the "trigger" causes the cams to move together so it can be inserted into a crack in the rock. Releasing the trigger allows the cams to expand, anchoring it into the rock. Now the rope can be attached to a sling and carabiner at the end of the stem. D) Kernmantle rope is rope constructed with its interior core (kern) protected with a woven exterior sheath (mantle) to optimize strength, durability, and flexibility. (Photos by Sarah Dunham.)
ists alike faced a long, arduous journey into Yosemite. Beginning in San Francisco, travelers boarded a ship heading up the San Joaquin River to Stockton. After their early morning arrival, travelers began a bumpy (and dusty) one-to-two-day stage journey to Mariposa, Coulterville, or Big Oak Flat. Most passengers who traveled this far were destined for Yosemite Valley, meaning the next part of their journey was two or three days on horseback navigating the narrow trails to the rim of the Valley. The final piece of the journey was the cliff-side route to the Valley Floor. Steep granite walls gave many travelers cause for concern. Road builders faced a formidable engineering challenge along this portion of the route.

Passengers on the Big Oak Flat Road were largely traveling down switchbacks built into the Diorite of the Rockslides. Routing the road through diorite has several impacts on the road and the travelers. Diorite has more numerous and more closely-spaced joints than granite (Figure 3.18). A high proportion of joints can be either a good thing or a bad thing, depending on what perspective one has. For the engineers of the road, the highly-fractured diorite was easier to blast away. But the numerous fractures in the rock also make it a hazard to the longevity of the road as well as a hazard to travelers because highly-fractured rock is more likely to fall, block the road, or injure someone.

Today, the Big Oak Flat Road is routed through the dense El Capitan Granite, one of the strongest rocks in the park.

Among the most formidable geologic obstacles to building roads and trails are the dense granite rocks and the steep, glacially-polished cliffs. Yosemite’s strong, dense granites can be seen as an obstacle or as a tool in trail and road building. A stoneman named John Conway brought the skill of rockwork to trail building in Yosemite in the 1920’s. Jim Snyder (Yosemite’s historian and archivist at the time) describes Conway’s approach as answering the question “How can I get from here to there, and what obstacles do I have to avoid?” Conway’s trails and roads hug the topog-
Why are ThereComparatively Few Rock Climbers at Mt. Rainier?

Most of Yosemite’s rocks and most of the rocks at Mt. Rainier, in Washington State, are igneous. Why is rock climbing at Mt. Rainier such a minor activity compared to Yosemite?

The igneous rocks at Yosemite are **intrusive (plutonic) rocks**, meaning they cooled slowly deep within the earth (Figure 5.3). As the magma slowly cooled, large mineral crystals grew over thousands of years and were closely packed into a dense, impermeable mass. The igneous rocks at Mt. Rainier are mostly **extrusive (volcanic) rocks**, meaning they cooled quickly after they were erupted onto the surface of the Earth. When magma cools quickly, it forms small crystals that you would need a magnifying glass to see or it does not form crystals at all. In some cases the resulting rock is full of air bubbles!

Rocks at Mt. Rainier are also different because they were deposited in layers while Yosemite’s rocks solidified into one uniform mass. Mt. Rainier is a composite volcano meaning its slopes are layers of not only lava flows, but also volcanic ash, mudflows, pumice, and other soft, light-weight materials. These materials make terrible climbing rocks because they are crumbly and are very sharp. Composite volcanoes in the Cascade Range, such as Mt. Rainier, Mt. St. Helens, Mt. Hood, Mt. Lassen, and Mt. Shasta, all have magma chambers underneath them today. Given a few million years, these magma chambers may be eroded and exposed at the surface like Yosemite’s granites are today.

When plutonic and volcanic rocks are exposed to the elements, they weather and erode differently. Unjointed granites are impermeable; that is, they lack connected spaces for water to flow through. Weathering rock relies on the presence of water, so weathering granite is slow because the water can’t penetrate the surface. As a result Yosemite’s landscape is dominated by steep, climber flecked, granite cliffs with small talus piles at the base. Volcanic rocks are more permeable, meaning water can get into the pore spaces and decompose the rock at a much faster pace than in plutonic rocks. The result is a shallower slope of eroded rock (scree) with large talus piles at the foot of the mountain.

Cliffs Dare Climbers

Steep, glacially-polished cliffs might be an obstacle to avoid when building a road or a trail, but they are a challenge to climbers who want to scale the cliffs. Yosemite’s high-silica rocks formed as magma deep beneath the surface of the Earth cooled and solidified. When magma solidifies within the crust, the overlying rock acts like a blanket, insulating the magma. As a result, the magma cools so slowly that large mineral crystals grow for thousands of years and form an interlocking structure that is strong enough to support the weight of a person. Climbers use large crystals to

What is “Free Climbing” Anyway?

Visitors often wonder about what is happening on big walls. There are three kinds of climbing:

- **Sport climbing** uses pre-placed bolts for faster ascents, traditional (trad) climbing involves placing and removing protection as you climb, and free soloing is the extremely focused act of climbing without ropes. “Free-climbing” can be any one of these types of climbing. It means that bolts (fall protection) are used for safety, but the bolts never support any of the climbers weight during the climb.

Figure 5.4. The pieces of fly rock between the cabins that contribute to Curry Village should serve as reminders that Yosemite is an active, unpredictable geologic landscape! (Photo by Sarah Dunham).
their advantage. Large mineral crystals make good hand and foot holds. The knobbier the rock, the easier it is to climb. The especially large mineral crystals are called “chicken heads” because that’s what they look like when they stick out of the wall.

When climbers first arrived in Yosemite Valley, walls like these had never been attempted. Yosemite’s walls offer a unique challenge; the granite is extremely monolithic, meaning there are few vertical and horizontal joints for traverse options. Monolithic walls are partially a result of the composition of the rocks. Climbing routes tend to be concentrated on silica-rich rocks (rocks that contain large amounts of quartz and feldspar). These rocks are stronger and tend to have more widely-spaced joints than rocks that contain more dark (mafic) minerals like biotite and hornblende (Figure 3.18). Grain size also affects the spacing of joints. Finer-grained rocks tend to have more closely spaced joints than coarse-grained rocks.

Vertical joints are responsible for the flat face of Half Dome and the parallel faces at Cathedral Rocks and the Three Brothers. Such a vast, smooth face also makes scaling Half Dome like trying to climb window glass. The flat joint-produced walls, like those of El Capitan and Leaning Tower, attract climbers on an international scale.

**Big-Wall Climbing Comes of Age in Yosemite**

The first roped climb in Yosemite occurred over Labor Day weekend in 1933 by a group of Sierra Club climbers. They hailed from the San Francisco Bay area and were some of the best-trained climbers of the day. Their destination was “Lunch Ledge” on Washington Column. Today, you’ll be hard pressed to find lunch ledge. It is a nondescriptive platform hidden by trees, but nonetheless, it marks the beginning of climbing’s evolution in the park.

The early climbers in the park were the true pioneers. They did some amazing routes considering they were outfitted with soft **pitons**, hemp ropes, and tennis shoes. New equipment helped make more routes possible. John Salathe’s steel pitons, Yvon Chouinard’s new-design **carabiners**, and Ray Jardine’s spring-loaded **camming devices** ("friends") are among some of the new equipment engineered and pioneered in Yosemite Valley.

*Figure 5.5. At 6:52pm on July 10, 1996, two large rock falls broke loose from the cliff below Glacier Point generating an airblast comparable to a tornado. The airblast was strong enough that it toppled 1000 trees! Immediately following the airblast a cloud of pulverized rock descended from the impact site into the Happy Isles area scouring trunks of standing trees. Sandy dust from the cloud rose quickly into the air and blocked the sun in the area near Happy Isles for several minutes. These photos were taken in sequence as the dust cloud moved down Yosemite Valley. (Photos by David F. Walter).*
Can You Predict a Rockfall?

Rockfalls are practically impossible to predict. Some rockfalls are associated with a trigger (for example, an earthquake, a period of heavy rainfall, or a large amount of snowmelt) but some have no identified trigger. Trigger or no trigger, the aftermath of rockfalls is obvious throughout Yosemite.

In Yosemite Valley rockfalls and debris flows with identified triggers make up about half of the records from 1851-1992. But some of the scariest rockfalls occur with no identified trigger. For example, on Wednesday, July 10, 1996 a large block of granite (80,000 tons, the weight of ~10,000 elephants), detached from the cliff above Happy Isles and freefell into Yosemite Valley (Figure 5.6). The impact of this amount of rock falling was enough for the rockfall to be registered on seismometers (instruments used to measure seismic waves that are normally caused by earthquakes) 30 miles away! Because the large block of granite hit parallel to the valley floor, it caused an airlift that traveled at a speed of 174 miles per hour (280 kilometers per hour). This was fast enough to flatten trees within a 10 acre (0.04 square kilometer) area of the impact site. Today trees are beginning to grow where the forest was flattened, but the talus pile is still visible through the trees. Over time, the talus will be masked by forest.

Other advances made a huge impact on sport climbing. Kernmantle rope, introduced in the 1950’s, was stronger and stretched more than the hemp and nylon ropes used by the early climbers. In 1980 Boreal introduced the first "sticky rubber" shoe that allowed climbers to scale cliffs more efficiently than before and also led to several new routes being established. (Figure 5.3)

“Crack climbing” is a unique strategy honed in Yosemite that exploits joints in the rock. It involves wedging your hands and feet inside cracks and working your way to the top of the crack. It is relatively easy to climb up a crack and can be relatively difficult to get from one crack to another.

As routes got more and more difficult, climbers instituted a rating system called the “Yosemite Decimal System” that expanded the original class system. According to the original system, Class 1 is a hiking scramble to a rocky gradient; generally hands are not needed. (Most hikes in Yosemite fall into this category.) Class 2 involves some scrambling and likely the use of hands. Many of the off-trail hikes, such as the user trail to the summit of Mt. Dana, fall into this category. Class 3 routes require simple climbing or scrambling and frequent use of hands. Some of the more difficult user trails in Yosemite, such as the trail to the summit of Mt. Lyell fall into this category. Class 4 climbs utilize a rope because of exposure; a fall could be serious or fatal. Class 5 climbs involve the use of rope and natural or artificial protection (for example, pitons and cams) to protect against a serious fall but not to aid in climbing. Class 6 climbs require placing the climber’s weight on the equipment itself, as opposed to using it only for protection.

Most of Yosemite’s climbs fall into the Class 5 category, where equipment is used for safety (free-climbing). Yosemite’s Class 5 climbs vary significantly in difficulty and necessitated further subdivision. Royal Robbins and Don Wilson first divided Class 5 climbs into subdivisions 5.0-5.9 depending on difficulty. This decimal system spread through California and the rest of the country by about 1956. Years later it became known as the “Yosemite Decimal System.” It is still widely used today.

Every Visitor Experiences Geology

Whether taking a break at Lunch Ledge or pulling off the road, at some point during the day visitors eat lunch and sometimes take a nap. Geological subtleties help us decide where to do these things. Geologists classify rocks in terms of what they are composed of and how they formed, giving them names such as granite, granodiorite, and diorite. But when on the lookout for a lunch spot, all rocks become potential “lunch rocks.” The best lunch rocks differ between visitors, but a good lunch rock is not hard to come by. There should be a comfortable place to sit and a great view. The Cathedral Peak granodiorite at Cathedral Lake has some of the best lunch rocks in the park. The large mineral crystals are interesting up close, and there is a fabulous view of Cathedral Lake and the Cathedral Peaks. Glaciers have polished the rock smooth so one can stretch out comfortably, and if it’s sunny it’s a good place to warm up after a swim.
It is important to remember that Yosemite is geologically active, so the view we have today may not be quite the same on our next visit. Rockfalls are dramatic geologic events that result from weathering and erosion. Several major prehistoric rockfalls are visible in Yosemite Valley: Devil’s Elbow near El Capitan, the tree-covered talus cone behind Curry Village, and the rock dam that forms Mirror Lake.

Rock falls are violent events, but the fallen rocks themselves don’t seem to be so scary. Some of the boulders that have traveled beyond the base of talus piles (fly rock) have been incorporated into the layout of buildings in Yosemite Valley. Part of the charm of Curry Village is that cabins are situated among the boulders of prehistoric rock falls (Figure 5.4). The boulder in Camp 4 has been a formidable challenge to climbers for decades. Similarly, fallen rocks near the Ahwahnee Hotel often have chalk marks left by the hands of climbers.

Living in a geologically-active area involves knowing what the risks are and how best to minimize those risks. In 1998, a team of scientists looked at rockfall hazard in Yosemite Valley. They identified two zones: talus slopes, where most of the rocks are concentrated, and shadow zones identified by boulders that had fallen from cliffs and traveled beyond the talus piles (Figure 5.5). Within most talus piles, rocks can be expected to fall every year or few years. Rocks that fall beyond the talus are less common, traveling that far only about every 1,000 years. Results from the study are important when determining where to put new buildings, but it is important that the results and the suggested hazard boundaries be taken as a guide, not as a guarantee of safety. Yosemite Valley is narrow and flanked by steep cliffs that are actively eroding, so there is really no 100% safe place to put a building!
Figure 5.6. Rock fall hazard map of Yosemite Valley (Modified from Wieczorek and others, 1998). Warm tones represent rockfalls, green tones rock slides, and blue and purple tones debris flows. Dark hues are recent events and light hues are prehistoric. Notice that most of the construction is out of the hazard zones but there are still some outlying areas inside the colored lobes that represent areas prone to rock fall hazards. It should be noted that this is a map of material that already has moved; it is not necessarily a prediction of where things might move in the future.
Appendix 1

Top Ten Geology-Related Questions Visitors ask in Yosemite National Park

1. What happened to the other half of Half Dome?
   We don’t know. The flat face of Half Dome follows a primary regional joint. It is common for flat pieces (slabs) of rock to break off parallel to joints. It is likely that the other half of Half Dome was removed over a long period of time as a series of small pieces via rockfall. These pieces may have been further broken down into smaller rocks and sedimentary particles that were transported down-valley by glaciers and streams that occupied Tenaya Canyon.

2. There were glaciers here, right?
   Yes. Moraines in the Yosemite Region record three episodes of glaciation. It is likely, however, that Yosemite was occupied more than just three times because glaciers are capable of erasing the evidence of past glaciations. The moraines preserved in Yosemite record the glaciation with the longest extent, the glaciation with the second longest extent, and the glaciation with the third longest extent.

3. What kind of rocks are in Yosemite?
   Most of the rocks in Yosemite are igneous, meaning they were produced when partially-molten rock (magma) cooled to form rock. Yosemite’s rocks are plutonic rocks, meaning they cooled slowly within the Earth. When partially molten material cools slowly, large crystals form. (Large crystals to a geologist are crystals you can see with just your eyes.) Prominent black and white mineral crystals in Yosemite’s rocks produce the salt-and-pepper appearance visitors often identify when given a granite and asked, “What do you see when you look at this rock?”

4. Are all the rocks in Yosemite granite?
   No, not all the rocks in Yosemite are granite. The word granite refers to a specific range of chemical composition and texture in igneous rocks. Most of the igneous rocks in Yosemite have a salt-and-pepper appearance, leading many visitors to the assumption that all the rocks are granite. Rocks with a salt-and-pepper appearance can be described as “granite-type” rocks. Darker rocks with less silica are called diorite. Many of the rocks have a chemical composition between that of granite and diorite, and are hence called granodiorite.

5. Can you predict a rockfall?
   Although the processes contributing to rockfalls are understood, rockfalls cannot be predicted. Geologists keep track of where rocks have fallen and produce rockfall hazard maps based on the observed patterns (Figure 5.6). Planners consult these maps when proposing new development in Yosemite.

6. What makes a hanging valley?
   A hanging valley is a tributary valley high above the main valley floor. Hanging valleys in Yosemite are commonly the sites of waterfalls such as Yosemite Falls. Hanging valleys were produced because the glaciers that occupied the smaller tributaries were smaller and had less erosive power than the glacier that occupied the main valley. As a result, the main valley was eroded more deeply than the smaller tributaries.

7. What exactly IS a monolith?
   A monolith is a massive, coherent, upright block of rock. El Capitan is among the largest granite monoliths in the world.

8. Is Half Dome a magma chamber?
   No one knows for sure. The rocks exposed in Yosemite provide no indication of the vent locations for the volcanoes. Half Dome may be a piece of a larger magma chamber that evolved over a period of at least 16 million years. The dome shape
of Half Dome is related to the initial surface topography and resulting exfoliation in the range.

9. **Why are there so many domes in Yosemite?**

The large monoliths and domes in Yosemite are the erosional remnants of massive, unjointed rock park-wide, and the large amounts of glacial polish in Tuolumne Meadows. Yosemite is famous for its large monoliths and domes but these features are not isolated to the park itself. The largest dome in the Sierra is the Tehipite Dome on the Middle Fork of the Kings river.

10. **How deep is the bedrock floor of Yosemite Valley?**

The floor of Yosemite Valley is flat because the bottom of the bedrock “U” is filled with sediment deposited in Ancient Lake Yosemite (Figure 3.1). The bedrock “U” is actually composed of three basins of varying depths. The deepest basin occurs between the Ahwahnee Hotel and Curry Village where the bedrock is 600 m (2,000 ft.) above sea level and is filled with 600 m (2,000 ft) of sediment, making today’s surface about 4,000 ft. (1,200 m) above sea level. Bedrock rises to 3,000 ft. (900 m.) above sea level near Rocky Point where the sediment on top is 1,000 ft. (300 m.) thick. The bedrock then deepens into the second basin 2,600 ft. (800 m.) above sea level near the Cathedral Spires and is covered by 1,300 ft. (400 m.) of sediment. The boundary between the second and third basin is at Artist Creek where the bedrock rises to 3,300 ft. (1,000 m) above sea level and is covered by 520 ft. (160 m.) of sediment. The bottom of the third basin is about 3,000 ft. (900 m.) above sea level near Cascade Creek where the bedrock emerges from under the blanket of sediment.

How do we know this? In the 1930’s researchers detonated dynamite to generate seismic waves that traveled down to the bedrock floor of Yosemite Valley, echoed off the bedrock, and arrived back at the surface. By measuring the time it took for the wave to travel down and then back up, scientists could calculate how much material the waves had to travel through and approximate the depth to bedrock in Yosemite Valley.
Appendix II

Sample Program Outlines

Geology Stroll (Variable Ages) by Ranger Sarah Dunham

Topic: Geology

Theme: Ancient geologic processes molded the landscape that attracts millions of visitors to Yosemite every year, and active geologic processes continue to affect life in Yosemite.

Goal: Visitors will appreciate the formation of Yosemite’s rocks and the processes that have sculpted and continue to sculpt them today.

Objectives: By the end of the program visitors will be able to:
- Appreciate that Yosemite’s granite-type rocks originated from magma.
- Identify different minerals in a rock.
- Understand that the bedrock floor of Yosemite Valley is deep under the surface they walk on.
- Recognize the importance of evaluating geologic processes for park planning and safety.

Materials:
- Earth Speaks by Steven VanMatre and Bill Weiler
- 10 (or so) granite-type rocks
- 10 (or so) each of hornblende, biotite, feldspar, and quartz crystals.
- Matthes Sketches of Yosemite Valley during Sherwin Stage, Tioga Stage, and Ancient Lake Yosemite Stage glaciations.
- Photos of the Big Tree Room and Barnard’s Rock Cottage.
- Photos of the aftermath of the flood in 1997.
- Washington, Oregon, and California state quarters.

Outline:
Ranger walks attract a highly-varied audience (one of my walks attracted a Geology PhD, retired business professionals, several junior rangers and a photographer). Because the audience is so varied, it is crucial that the program appeal to universal intangibles.

At the Yosemite Valley Visitor Center:
During the opening of my program I like to ask visitors what Yosemite is to them. The answers vary, but inevitably some geological features such as cliffs, waterfalls, and the flat bottom of the valley make the list. This serves two purposes: first to allow visitors to express their own feelings and values to the group, and second to give me some insight into what they are curious about or identify with. Then I read the poem “A Sense of Place” by Alan Gussow and talk about the importance of Yosemite as a place, the process of experiencing deeply, and encourage visitors to connect with something from the visitor center to the first stop. I often pose the question “Where did these cliffs come from?” as the beginning of a transition.

Stop 1: Black Oak trees just before the start of the boardwalk at Cooks Meadow
I always begin at this stop by pointing out the major landmarks: Half Dome, Sentinel Rock, and Yosemite Falls and then asking the question “Where did these cliffs come from?” There are various answers: glaciers; magic; subduction; or something of the like. Usually there is an opening to begin discussions of plate tectonics, subduction, volcanic eruptions, and slow cooling of plutonic rocks. To make the rocks more real in the meadow, I bring granite, biotite, hornblende, feldspar, and quartz to pass around. (The more samples the better in this case, especially during the busy summer months.) I follow up with the question: Where did the volcanoes go? A discussion of weathering, erosion, and deposition follows with an emphasis on rivers cutting V-shaped canyons. Using the Washington (Mt. Rainier), Oregon (Crater Lake), and California (Half Dome) state quarters to illustrate
this process is fun and effective (See Fig. 2.9). To build the transition from this stop to the next, I ask visitors to study the shape of the Valley as we walk across the footbridge to the clearing in the pines.

**Stop 2: Ponderosa Pine Clearing on the far side of Cooks Meadow**

To expand the transition question, I ask several visitors to describe what they see—shapes, colors, patterns, etc. Someone usually hits on the broad, steep-sided valley with a flat bottom and often makes the connection between the shape of the valley and the glacier that sculpted it. I try to expand this by talking about the formation of glaciers and the erosive power of glaciers. To demonstrate this, visitors and I do the “Yosemite handshake” (see Fig. 3.10). At this point we look for other evidence of glaciers—trimlines, moraines, etc. I talk about Ancient Lake Yosemite and have visitors imagine what the lake would have looked like. Drawing parallels between Ancient Lake Yosemite and Mirror Lake tend to be illustrative, especially with a few historical photos.

At this point everyone seems to be in a science mindset so we look out and remember why we came to the park and think about what we did or will do while we’re here. I ask visitors to think about how geology influenced their reasons for coming on their journey into the park as we move from this stop to the next.

**Stop 3: Markers for the Big Tree Room**

Someone usually finds the markers before the group gathers. If someone is looking at the markers, I’ll squat down and ask about what they see. We’ll look at the marker and I’ll show pictures of the inside and outside of the Big Tree Room in Hutching’s House, Oak Cottage, and Rock Cottage. When I show the pictures of Rock Cottage I always point out the rocks around the edge of the cottage and ask where the rocks came from. This opens the door for a discussion of weathering and rockfall. We usually agree that close to a talus pile is a bad place to put a building (universal concept: safety) and I’ll ask visitors to think about if the whole floor of Yosemite Valley is a better place to put a building. Why or why not.

**Stop 4: Over Superintendent’s Bridge**

As we walk over the bridge, I’ll slow down and look at the sign marking the high water levels of various floods in Yosemite’s history. Once we gather on the far side of the bridge we talk about flooding. I use the flood in 1997 (and the high water marker on Superintendent’s Bridge) as an example. We talk about rain-on-snow events that cause flooding in the park, duration, and damage. Among the universal concepts visited here are safety, survival, and death.

Because the last two stops are about where not to put a building, I like to show a map from a building plan that shows new construction between the talus line and the high water mark from the flood of 1997. (You can find obsolete planning documents in the public information office and if you ask nicely they may let you have one; just make sure to say that it’s obsolete when you use it in a program). To end the walk I recap what we have talked about and share something that has captured me that week and contributed to my Yosemite.

46
Valley Floor Tram Tour  
(Variable Ages)  

by Ranger Sarah Dunham

**Topic:** An introduction to Yosemite Valley including geology, rock climbing, Yosemite Indians, fire, and bears.

**Theme:** Yosemite’s inspiring landscape is an unfinished sculpture with many artists, including dynamic natural processes and human interactions.

**Goal:** Visitors will appreciate the interconnectedness of the geological, natural, and human aspects of Yosemite Valley.

**Objective:** By the end of the program visitors will be able to:

- Identify El Capitan, Bridalveil Fall, Yosemite Falls, and Half Dome.
- Describe the significance of a glacial moraine.
- Appreciate that fire is an active participant in Yosemite’s ecosystem.
- Understand why it is important to store food properly.

**Materials:** Historical photos taken from Glacier Point, 1866 and on the Gibbon’s Survey, 1943.

**Outline:**

**I. Yosemite Lodge**

A. Introductions/Safety

B. Welcome to Yosemite National Park
   - Introduce theme:
     a. Landscape is a squishy term.

C. Preview of what is to come
   - Generate excitement: volcanoes, glaciers, floods, bears, birds, wagons, Indians, pioneers, and you!

**Transition:** One of today’s most visible human interactions with Yosemite’s inspiring landscape is rock climbing.

**II. Camp 4: National Historic place (evolution of climbing).**

A. Rock climbers and history of Camp 4
   - Climbers asked the questions: can we climb the wall?; then can we climb the wall without leaving all our gear behind?; and finally how fast can we climb the wall?

**Transition:** Climbers try to get to the top of the rocks, but the rocks themselves are trying to fall to the bottom of the slope.

**III. Three Brothers and Rocky Point**

A. Rockfall is an active process in this area: large talus piles near the road. (March 1987, large rockfall 600,000 m$^3$ blocked the road.)
   - Joints: zones of weakness in the rocks
   - Role of water and vegetation in rockfall

B. Point out Cathedral Spires and Rocks: examples of jointing.

**Transition:** As we make our way through Yosemite Valley, you may notice many of the rocks look very similar to each other. This is because similar processes formed them.

**IV. On the way to Devil’s Elbow and along El Capitan Straight**

A. Plate tectonics
   - Yosemite’s rocks were formed at a convergent plate boundary (Figure 2.5).
     a. Subduction, magma generation, and slow cooling.
   - El Capitan Granite is one of the strongest granites in the park so it stands up to erosion to produce one of the largest solid masses of granite in the world.
   - Devil’s Elbow
     a. Created by a long run rockfall. Similar to what is happening on Hwy. 140.

B. Point out the tree in the eye of El Cap
   - Tree inside is a pine and is ~80 feet tall, about the size of the trees closest to us, and over 250 years old.
   - Early soldier thought El Cap was 400 ft. tall.

**Transition:** The steep vertical face formed by the El Capitan granite is a prime location for rock climbers.

**V. El Capitan Stop**
A. Features and stats of El Capitan
B. Ascents
C. Gear and supplies for a climb
D. El Capitan Meadow is a good example of a pre-1850 meadow.

Transition: as you look around today, meadows and forests dominate the landscape. 10 Million years ago, before humans entered the valley, the landscape looked very different...

VI. El Capitan Meadow to Valley View
A. Uplift of the Sierras like a “trapped door” (fig. 2.14).
B. River downcuts forming a V-shaped valley
C. Glaciation of Yosemite Valley
   i. Point out El Cap Moraine. (20,000 years ago)
      a. compacts and forms a river of flowing ice.
      b. Nunataks
         • Half Dome, Sentinel Dome, and the top of El Capitan were nunataks.
   ii. Glaciers act like a bulldozer changing the V-shaped valley into a U-shaped valley (Fig. 3.9).
      a. The force from the 3,000 ft. of flowing ice pulls loose rocks from the valley walls and floor and freezes them in the ice.
         • The resulting mass of rocks and ice is like rocky road ice cream. (Ice cream represents the ice, and chunks represent the rocks entrained in the ice.)
      • Point out Bridalveil Fall as an example of a U-shaped valley.
      b. The flowing ice acts like a conveyor belt pushing all the rocks to the end of the glacier.
D. Moraines (Fig. 3.11)
   i. Glaciers can get bigger, get smaller, or be at equilibrium (stay the same size). In all cases the conveyor belt is still working.
   ii. Moraines occur when ice stagnates and the conveyor belt continues to work forming a large pile of rocks.
E. Glacial Lake Yosemite
   i. As the glacier recedes, the moraine acts as a dam trapping the melt water. Water carries sand and rocks with it. Sediment fills in the U-shaped valley.

This forms the flat bottom we see today (Figure 3.19).

Transition: Water in both its solid and liquid form has a huge influence on the landforms in Yosemite. At Valley View you can all take in the geological artwork we’ve thought about so far.

VII. Valley View Stop
A. Safety
B. If you have questions please feel free to ask them.

Transition: Notice the sign indicating the high water mark of the flood of 1997. Try to imagine what it would have been like to have been there when it happened.

VIII. Valley View Stop to Pohono bridge
A. Flooding is a natural process in Yosemite.
B. Flood of 1997
   i. Rain on snow event (up to 11,000 ft.) caused rivers to overflow.
C. Gauging station
   i. Measures volume, velocity, and depth.
   ii. One of the oldest gauging stations in California; has been recording since 1917 (almost 100 years on data)

Transition: These changes in flow generated by changes in climate can be seen in all the waterways in the park no matter how small.

IX. Pohono Bridge to Bridalveil Turn
A. Consider all the tributaries that flow into the Merced; they are all important, no matter how small.
   i. Bridalveil Fall
   ii. Ribbon Fall
   iii. Fern Spring: one of the smallest
      a. CCC in Yosemite
B. Other influential men also spent time in Yosemite.
   i. In 1903, John Muir and Teddy Roosevelt camped here and discussed the future of Yosemite.
C. Imagine how difficult the trek into the valley was for those influential men or for the first visitors into the valley.

Transition: Think about your journey into Yosemite.

X. Bridalveil Turn to Tunnel View
A. Warn about pedal to the metal
B. Wagon roads and the race to the valley floor
i. Wawona Road
   a. Tolls were $1/hiker, $2/carriage with one horse, $4/carriage with 4 horses, up to $12/carriage with 6 horses.
   b. Attracted visitors using the Giant Sequoias en route.

ii. Big Oak Flat Road (July 1874)
   a. Came into the north side of the valley.

iii. Coulterville (pronounced Colterville) Road (June 1874)
   a. Came into the north side of the valley.
   b. First road to reach the valley floor

iv. Early roads were so narrow that if two stages came in contact with one another, they couldn’t pass. Drivers would disassemble the stage move the parts and reassemble the stage on the other side. Takes 4-8 hours.

v. Early trips on stagecoaches would take 3-5 days.

Transition: At our next stop (Tunnel View & Discovery View), we’ll get out for a ~10 minutes. There is water if you’re thirsty. I have some pictures showing how the valley floor has been changing over the last 100+ years. If you’re interested or have questions, I’ll be available in the shade.

XI. Tunnel View to Bridalveil Straight
A. Yosemite has multiple inspiration points. This may be because visitors using different modes of transportation first view the valley from different places.
B. Even though the early visitors took different routes into the valley, they viewed much of the same scenery, flora and fauna.
   i. My favorite birds: bald eagles, peregrine falcons, and great gray owls.
      a. Peregrine falcons: a success story!
      b. Great Gray Owls: safety.
   ii. Take note of the forest, it Forest is dominated by conifers.

Transition: Early inhabitants of the valley used these resources to their advantage.

XII. Bridalveil Straight to Three Brothers viewpoint
A. Ahwahneechees were the first nations in the valley.
   i. Related to the Miwok and Paiute tribes of today.
   ii. Oldest archaeological evidence of people is about 8,000 years ago.
      a. Trade across the Sierra: obsidian.

B. Ahwahneechee were experts at living in the valley. Used the resources and processes to their advantage.
   i. Black Oak acorns provided up to 60% of the Ahwahneechee diet: grind into flour to make acorn mush (the texture of oatmeal, acquired taste).
   ii. Burning meadows for forest health.

C. Meadows also made it difficult for other tribes to ambush the Ahwahneechee.
   i. Mention El Cap meadow across the river.

Transition: To early pioneers fire was a threat.

XIII. Three Brothers Vista to Four Mile Trailhead
A. Mariposa Battalion (1851)
   i. Formed to relocate Indians who had raided prospectors.

B. As Yosemite’s fame spread, more buildings, livestock, and orchards planted to accommodate tourism.

C. Fire Suppression began in the 1860’s
   i. Resulted in overgrown forest
      a. Loss of park-like atmosphere experienced by the early residents of the valley.
      ii. More catastrophic fires that climb the “fuel ladders” into the canopy.

D. 1970’s Forest Restoration Project
   i. Recurrence interval of large fires ranges between 1 and 36 years.
   ii. Forest thinning
      a. “Miles of piles”
   iii. Prescribed burning.
      a. Opens canopy, reduces fuel, and facilitates nutrient cycling.

Transition: Isolated natural landscapes are easier to find than you think. 95% of the park is designated wilderness.

XIV. Four Mile Trail to Sentinel Bridge
A. What is wilderness? Why is it important? SHOUT out the answers…
B. Organic Act: "... to conserve the scenery and the natural and historic objects and the wildlife therein and to provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired for the enjoyment of future generations."
C. Point out Yosemite Falls and meadow. Slow for a picture.

Transition: Natural phenomena and processes are active everywhere in the park. We cannot and should not control natural phenomena and processes.

XV. Sentinel Bridge to Stoneman Bridge
A. The Yosemite Chapel is the oldest structure in Yosemite Valley. It is the only remaining building of Old Yosemite Village.
   i. Flo Hutchings
B. Hidden Giant sequoia trees on the landscape
C. Hidden Giant sequoia trees on my uniform

Transition: Most of the concessions are concentrated in this area of the valley.

XVI. Stoneman Bridge to Happy Isles
A. Orientation of natural features
B. Facilities and services in Curry Village
C. Orientation of campground
   i. Proper food storage: definition of food and use of bear boxes.
   ii. Feeding shows and open dumps
D. Happy Isles
   i. Nature center: great place to go with kids (where the Junior Ranger programs are held).

Transition: The Mist Trail is one of the most popular trail in Yosemite.

XVII. Happy Isles to Stoneman Bridge
A. Natural Quiet
B. Sierra Symphony
C. Mirror Lake
D. Mule riding at the stables
E. Camping is a celebrated way to experience Yosemite
   i. What do you do is a bear does come into your campsite?
      a. Give it a negative experience: look big and make lots of noise.
      ii. Part of my job today is to chase bears out of your campsite.

Transition: Camp Curry is part of the Yosemite experience for many people. However, the Camp Curry experience is not the same as it used to be.

XX. Ahwahnee Hotel
A. Good example of “parchitecture”
B. Built at the suggestion of Stephen Mather, director of NPS to attract the wealthy to the park. Opened in 1927
C. It’s worth checking out even if you’re not staying there because the interior is phenomenal!

Transition: Most of the concessions are localized in distinct areas like Curry Village, Happy Isles, and Yosemite Village. Concentration of concessions in these areas is done to provide easy access and to reduce traffic and impact in the valley.

XXI. Yosemite Village
A. Day use parking: used to be Camp 6.
B. Buildings in the Valley
C. Ranger Club

Transition: Yosemite is a complex and inspiring landscape of which we are a part. It continues to change because of natural processes but also because we are here interacting with it.

XXII. Yosemite Village to Yosemite Falls
A. Lower Yosemite Falls Project

Transition: Keep your eyes open and see how people will continue to affect the landscape.

XXIII. Yosemite Lodge
A. Have fun (and be safe) discovering your Yosemite.
B. Make sure to ask questions and continue learning.
abrasion: The wearing and grinding of rock surfaces by friction and impact. Glacial abrasion occurs when rocks and other sedimentary particles frozen into the base of a glacier are dragged over bedrock.

asthenosphere: The weak and plastic (like silly putty) layer of Earth’s mantle below the harder lithosphere.

atom: The simplest unit of a chemical element.

batholith: A large intrusive igneous rock mass having more than 40 mi² (100 km²) of surface exposure and no known bottom.

bedrock: Solid rock underlying loose sediment.

belay: In rock climbing, one climber will control the rope so that a falling climber will not fall very far.

biotite: A mineral composed of iron and magnesium rich silicate layers.

camming device: (see also friend): A piece of rock climbing equipment inserted into a crack and expanded so that a climbing rope can be attached to a sling and carabiner at the stem protruding from the crack.

carabiner: A metal loop with a spring loaded or screwed opening often used to quickly connect components in safety systems during a climb.

chattter mark: A series of crescent-shaped marks chipped away by tools frozen into the base of a glacier.

chemical weathering: The chemical decomposition of rocks and minerals through exposure to air, water, and other chemicals in the environment.

cirque: A deep steep-walled recess or hollow, horse-shoe-shaped or semicircular in map view. Generally situated on the side of a mountain produced by the erosive action of a glacier.

composite volcano: A large (up to 12 mile [20 kilometer] diameter) mountain formed during several eruptions of a variety of volcanic materials including lava flows, ash, pumice, cinders, and mudflows that pile up into a steep-sided volcano. (Also known as a strato-volcano.)

convection: A process whereby heat is transported via the physical movement of material.

convergent plate boundary: A region where two slabs of Earth’s outer shell (lithosphere) move toward one another, deforming, and destroying lithosphere. Subduction zones are a common manifestation of this situation.

core: The central portion of Earth beginning about 2900 km (1,800 miles) below the surface. It probably consists of a dense iron-nickel alloy.

country rock: The material enclosing or traversed by an igneous intrusion.

crescentic gouges: Crescent-shaped marks formed when large rocks frozen into the glacier are pushed down on bedrock, creating a conical fracture. The steep side of the gouge indicates the direction ice was flowing from.

crust: The outermost layer of Earth. It consists largely of relatively low-density rocks rich in silica and constitutes less than 0.1% of Earth’s total volume.

debris flow: A mass movement of rock, mud, and other surficial Earth materials where the material behaves like a fluid.

deposit: An accumulation of rock-forming materials by any natural process.

diagenesis: Any chemical, physical, or biological change that a sedimentary deposit undergoes culminating in the transition from sediment to sedimentary rock.

dike: A body of igneous rock that cuts discordantly through existing rocks.

divergent plate boundary: A region where two slabs of Earth’s outer shell (lithosphere) are pulling apart from one another, creating new lithosphere. Continental rift zones such as the East African Rift and the Basin and Range Province along with ocean features such as the Mid-Atlantic Ridge and East Pacific Rise are manifestations of this situation.

dome: A symmetrical, smoothly rounded rock mass that resembles a dome on a building generally formed via exfoliation. (For example, North Dome, Sentinel Dome.)
**ductile deformation**: A process whereby a rock or mineral changes shape but remains pliable during the process. (See also plastic deformation).

**element**: A substance that cannot be decomposed into another substance except by radioactive processes. An element is defined by the number of protons (positive particles) it contains.

**end moraine**: The outermost end moraine of a glacier. Marks the farthest advance of ice. (See also terminal moraine.)

**erosion**: The wearing away of soil and rock by land slide, rockfall, and the action of streams, glaciers, wind, and underground water.

**erratic**: A rock that was transported by a glacier and deposited a great distance from the place it originated. A true erratic is a rock of a different type than the rock it rests on.

**exfoliation**: The stripping of layers or shells of rock from the bare surface of a large mass of rock. This process is responsible for the dome shape of some of the landforms in Yosemite. (Cf: spheroidal weathering)

**extrusive rock**: (See also volcanic rock): An igneous rock that solidified from magma that erupted on Earth’s surface, forming fine-grained mineral crystals.

**fault**: A crack (or series of parallel cracks) where there has been movement of one side relative to the other in a direction parallel to the crack.

**Feldspar**: A common, often rectangular, mineral in an igneous rock.

**felsic**: A term that describes an igneous rock rich in silica.

**fimr**: A transitional zone between snow and glacial ice. Snow becomes firn after existing through one summer melt season.

**friend (see also camming device)**: A piece of rock climbing equipment inserted into a crack and expanded so that a climbing rope can be attached to a carabiner at the stem protruding from the crack.

**frost wedging**: A process in which water freezes in a crack in rock and the expansion tears the rock apart.

**geology**: The study of planet Earth.

**geomorphology**: The science investigating the general configuration and the processes that affect Earth’s surface.

**glacial ice**: Firn compresses farther causing the snow crystals to pack closer together. Eventually water no longer propagates through.

**glacial polish**: The smooth, even surface produced on bedrock by the abrasion (sandpapering) of sediment-laden ice.

**glacier**: A large mass of ice, rock, and other sedimentary particles formed by the accumulation, compaction, and recrystallization of snow, which moves downslope or outward from the weight and stress of its own mass.

**glaciology**: The study of the physics of glaciers.

**granite**: 1. (Sensu Stricto) A plutonic rock made up of 10-50% quartz, and the alkali feldspar/total feldspar ratio is 65-90%. 2. (Sensu Lato) Any quartz bearing rock composed entirely of crystals.

**granodiorite**: An plutonic rock similar to granite, but contains more plagioclase than potassium feldspar. It usually contains abundant biotite mica and hornblende, giving it a darker appearance than granite.

**grus**: Crumbled granite that forms by physical weathering. Grus is often the slippery sand on trails.

**hornblende**: A term used to refer to a group of dark minerals with a chain-like structure.

**hydration**: The incorporation of water into the structure of a mineral forming a new mineral.

**hydrolysis**: A decomposition reaction involving water, for example, “bloated Biotite.”

**hypothesis**: A testable, educated explanation for something. Evidence collected either supports or refutes a hypothesis.

**igneous rock**: Rock that solidified from molten or partially molten material (i.e., magma).

**intrusive rock**: (See also pluten): An igneous rock that solidified from magma that cooled within the Earth, generally forming coarse-grained mineral crystals.

**isostasy**: A condition where a buoyant force pushing Earth materials up is balanced by an equal gravitational force (weight) pushing downward.
isostatic equilibrium: A state of isostasy, achieved when upward and downward forces are equal.

joint: A crack in a rock where there is no movement. A regional joint extends over several miles.

joint set: A group of parallel joints.

kernmantle rope: Climbing rope constructed with its interior core (kern) protected with a woven exterior sheath (mantle).

lateral moraine: A moraine deposited at the side of a glacier.

lithification: the formation of sedimentary rocks through sediment compaction and cementation.

lithosphere: The rigid layer of crust and mantle comprising the tectonic plates that overly and move across the softer asthenosphere.

mafic: A term that describes igneous rocks that are low in silica.

magma: molten material below or within Earth’s crust from which igneous rock is formed by cooling.

magmatism: The motion or activity of magma.

mantle: The portion of the Earth between the crust and the core, made of minerals rich in silica, iron, and magnesium.

mechanical weathering: The disintegration of rock into smaller pieces by physical processes.

medial moraine: A moraine deposited at the confluence of two glaciers. Medial moraines are most often parallel to lateral moraines.

megacryst: a mineral crystal that is significantly larger than the surrounding crystals.

metamorphic rock: A rock formed through the recrystallization of a preexisting rock, while the rock was still solid.

mineral: Minerals are the building blocks of rock; they are the salt and pepper pieces you see in Yosemite’s granites. Technically, a mineral is a naturally occurring, inorganic substance that has a unique chemical composition and an organized internal structure.

mineralogy: The composition of a rock determined by the amounts of minerals it contains.

molecule: A group of atoms bonded together forming the simplest unit of a chemical compound such as a mineral.

monolith: A large, unjointed block of rock, usually upright.

moraine: A mound or ridge of till (chaotic mixture of clay, silt, sand, gravel, and boulders) deposited by a glacier.

moulin: A narrow, tubular chute, hole, or crevasse through which water enters a glacier from the surface. Moulins can be deep enough for water to reach bedrock.

nunatak: The exposed summit of a ridge, mountain, or peak not covered with ice or snow in an ice field or glacier.

outcrop: A rock formation that is visible on Earth’s surface.

outwash plain: When glaciers melt they release a large volume of meltwater that spreads out into a sheet and deposits till.

oxidation: A chemical reaction whereby minerals react with oxygen in the atmosphere and produce new minerals. Rusty-colored streaks on cliff faces are the result of oxidation reactions.

petrology: The branch of geology dealing with the origin, occurrence, structure, and history of rocks.

phenocryst: Mineral crystals that are larger than the majority of the surrounding matrix.

piton: A peg or spike driven into a rock or crack to support a climber or rope.

plagioclase: A feldspar that contains large amounts of sodium and calcium relative to potassium.

plastic deformation: See ductile deformation.

plate tectonics: The theory that features on Earth’s surface result from the horizontal movements of large slabs of Earth’s outer shell (lithosphere).
pluck: (See also quarry) A process of glacial erosion where blocks of bedrock are detached and transported from their source by the motion of a glacier.

pluton: An igneous rock that intrudes and solidifies under the surface of the Earth.

plutonism: describes the pluton emplacement during times of magmatic activity.

porphyry: An igneous rock with a porphyritic texture.

porphyritic: a textural term that describes a rock composed of large mineral crystals surrounded by a finer-grained mineral matrix. Rocks that are dominantly porphyritic are termed porphyry, for example the Johnson granite porphyry.

potassium feldspar: A feldspar that contains large amounts of the element potassium relative to the elements calcium or sodium.

pothole: A cylindrical pit formed from the whirling of loose stones trapped within strong rapids or waterfalls.

pumice: A felsic, porous volcanic rock that forms from the solidification of a frothy, glass-rich magma.

quarry: (See also pluck.) A process of glacial erosion whereby blocks of bedrock are fragmented and loosened from their source by high-pressure gradients associated with the motion of a glacier.

quartz: A mineral composed of pure silica.

radiometric dating: Determining the age in years of an object by measuring the amount of radioactive elements and their decay products.

recessional moraine: A moraine built during a pause in the final retreat of a glacier. These moraines may also represent a slight advance of the glacier during the overall period of recession.

rift: A region of Earth’s surface where the crust and uppermost mantle (lithosphere) are being pulled apart.

rock: A mixture of minerals that are interlocked or cemented together naturally.

rouche moutinée: A glacially-sculpted knob of bedrock. Its long dimension is oriented with the direction of ice flow; the rounded, striated upstream side slopes gently while the downstream-side is steep and rough in texture. These features were named by French visitors to the region. Rouche moutinée means “sheep rock.”

sediment: Material eroded from preexisting rocks that is transported and deposited elsewhere.

sedimentary rock: A rock formed from the burial and cementation of eroded rock fragments, or from material precipitated through biological or chemical activity.

sheet joint: Arcuate cracks in monolithic rocks that form as a result of the release of overlying compressive stress. Sheet joints form parallel to the exposed rock surface and are responsible smooth domes. (See also exfoliation.)

silica: An ion consisting of the elements silicon and oxygen that combines with other elements to form most of the minerals in Earth’s crust and mantle.

silicate: A mineral rich in silica.

strato-volcano: A large (up to 12 mile [20 kilometer] diameter) mountain formed during several eruptions of a variety of volcanic materials including lava flows, ash, pumice, cinders, and mudflows that pile up into a steep-sided volcano. (Also known as a composite volcano.)

striation: Generally parallel scratches on a bedrock surface by a glacier.

subduction zone: a feature formed when an oceanic plate and a continental plate collide and the oceanic plate sinks (subducts) below the continental plate.

talus: An accumulation of loose, angular rocks at the base of a cliff.

tectonic stress: Tension exerted on the lithosphere by the motion of tectonic plates.

terminal moraine: The outermost end moraine of a glacier. Marks the farthest advance of ice.

terminus: The outer margin of a glacier.

till: Sediment deposited by glacial ice.

tool: A solid object, commonly rock, dragged along the bed of a glacier by the flowing ice.

transform plate boundary: A region where two slabs of Earth’s outer shell (lithosphere) slide laterally past one another.
transportation: The movement of sediment by flowing water, ice, wind, or gravity.

trimline: A change in character of rock that marks the upper extent of a glacier.

user trail: A trail that is used by visitors but is not patrolled or maintained by the NPS.

vent: An opening on Earth’s surface where lava is extruded. A vent often coincides with the top of a volcano.

volcanic rock: (See also extrusive rock). An igneous rock that solidified from magma that erupted on Earth’s surface.

volcanism: The eruption and outflow of molten rock material (magma) onto the surface of the Earth.

weathering: The physical and chemical processes that disintegrate rock but do not move it to a new physical location.

windward side: The direction from which the wind is blowing at the time in question. Opposite of leeward side.
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