National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Pinnacles National Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2022/2471

ON THE COVER
Photograph of Bear Gulch looking north from Toprope Rock ("The Camel") with the top of Discovery Wall visible on the left.
Photograph by Rebecca Port (National Park Service).

THIS PAGE
Photograph of the namesake spires of the Pinnacles Volcanic Formation. Weathering of ancient volcanic material produces a distinctive landscape at Pinnacles National Park.
Photograph by Rebecca Port (National Park Service).

Pinnacles National Park

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October 2022

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

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

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

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Please cite this publication as:

Barthelmes, M. 2022. Pinnacles National Park: Geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2022/2471. National Park Service, Fort Collins, Colorado. https://doi.org/10.36967/2294842.

NPS 114/186433, October 2022

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Executive Summary

Comprehensive park management to fulfill the mission of the National Park Service (NPS) requires an accurate inventory of the geologic features of a park unit, but park managers may not have the necessary information, geologic expertise, or means to complete such an undertaking; therefore, the Geologic Resources Inventory (GRI) provides information and resources to help park managers make decisions for visitor safety, planning and protection of infrastructure, and preservation of natural and cultural resources. Information in the GRI report may also be useful for interpretation.

Pinnacles National Park stands out in California for its geologic features and story. Visitors can traverse talus caves, hike along sheer cliffs and between towering spires of rock, and witness firsthand physical evidence that provided critical support for the theory of plate tectonics. This stunning landscape also provides habitat for rare and wonderful species; from bats that dwell in the talus caves to California condors that roost on the tall pinnacles. The geologic story of the park is rich enough to fill a textbook, with evidence of geologic processes including intrusive and extrusive volcanism, marine deposition, faulting and folding, caves, and most notably, significant movement along the San Andreas Fault.

Such a smorgasbord of geologic features and processes, however, comes with its own smorgasbord of management challenges. Preserving and protecting a landscape for the enjoyment of generations to come includes understanding geologic hazards and minimizing their potential impact on staff, visitors, and facilities; and protecting geologic features from degradation caused by visitor use. Rocks fall, streams flood, and the delicate habitats of endangered and protected species are vigorously explored by the curious. Understanding the geologic resources within the park is necessary to successfully managing them. This report summarizes the history and significance of those resources, describes the existing features and processes, highlights the potential management challenges, and provides guidance to meet those challenges.

The GRI report consists of the following 6 chapters:

Introduction to the Geologic Resources Inventory—This chapter provides background information about the GRI, highlights the GRI process and products, and recognizes GRI collaborators. A geologic map in GIS format is the principal deliverable of the GRI. Three geologic maps—the GRI does not conduct original mapping—provided the source information for the GRI GIS data for Pinnacles National Park. The data was compiled by the GRI in 2010 and updated in 2022. The GRI GIS data may be updated again if new, more accurate geologic maps become available or if software advances require an update to the digital format. This chapter also calls attention to the poster that illustrates these data.

Geologic Heritage of Pinnacles National Park—This chapter highlights the geologic heritage values of the geologic features, landforms, landscapes, and stories of the park. It also draws connections between geologic resources and other park resources and stories.

Geologic History—This chapter describes the chronology of geologic events that formed the present landscape. It sets the stage to understand the features and processes within the park and may provide information useful for interpretation.

Geologic Features and Processes—This chapter describes the geologic features and processes of significance for the park and highlights them in a context of geologic time. The features and processes are discussed in order of geologic time, oldest to youngest, and include Pinnacles Volcanic Formation; talus caves; faults and folds; fluvial features and processes; groundwater and springs; lakes; paleontological resources; and periglacial features.

Geologic Resource Management Issues—This chapter discusses management issues related to the park's geologic resources (features and processes). Issues, which are discussed in order of management priority, are seismicity and earthquakes; cave management; flooding; climate change; slope movements; rock climbing; disturbed lands (hydrology and watershed management); groundwater and springs; paleontological resources; oil, gas, and mineral development; and the documentation and reclamation of abandoned mineral lands.

Guidance for Geologic Resource Management—This chapter is a follow up to the "Geologic Resource Management Issues" chapter. It provides resource managers with a variety of ways to find and receive management assistance with geologic resources.

Literature Cited—This chapter is a bibliography of references cited in this GRI report. Many of the cited references are available online, as indicated by an

Internet address included as part of the reference citation. If park managers are interested in other investigations and/or a broader search of the scientific literature, the NPS Geologic Resources Division has collaborated with—and funded—the NPS Technical Information Center (TIC) to maintain a subscription to GeoRef (the premier online geologic citation database). Multiple portals are available for NPS staff to access this database. Park staff may contact the GRI team or the NPS Geologic Resources Division for instructions to access GeoRef.

Introduction to the Geologic Resources Inventory

The Geologic Resources Inventory (GRI), which is administered by the Geologic Resources Division (GRD) of the NPS Natural Resource Stewardship and Science Directorate, provides geologic map data and pertinent geologic information to support resource management and science-informed decision making in more than 270 natural resource parks throughout the National Park System. The GRI is funded by the NPS Inventory and Monitoring Program.

GRI Products

The GRI team—which is a collaboration between GRD staff and research associates at Colorado State University Department of Geosciences and University of Alaska Museum of the North—completed the following tasks as part of the GRI process for Pinnacles National Park: (1) conducted a scoping meeting and provided a scoping summary (KellerLynn 2008), (2) provided digital geologic map data in a geographic information system (GIS), (3) created a poster to display the GRI GIS data, and (4) provided a GRI report (this document). GRI products—GIS data, map posters, scoping summaries, and reports—are available on the "Geologic Resources Inventory—Products" website and through the NPS Integrated Resource Management Applications (IRMA) portal (see "Access to GRI Products").

Information provided in GRI products is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based upon the information provided in GRI products. Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features in the GRI GIS data or on the poster. Based on the source map scales (1:100,000 for Wagner et al. 2002 and Rosenberg and Wills 2016; and 1:24,000 for Matthews 1973) and *Map Accuracy Standards* (US Geological Survey 1999), geologic features represented in the GRI are expected to be horizontally within 51 m (167 ft) and 12 m (40 ft), respectively, of their true locations.

GRI Scoping Meeting

On 25 September 2007, the National Park Service held a scoping meeting at Pinnacles National Park (then Pinnacles National Monument) in Paicines, California. The scoping meeting brought together park staff and geologic experts, who reviewed and assessed available geologic maps, developed a geologic mapping plan, and discussed geologic features, processes, and resource management issues to be included in the final GRI report. A scoping summary (KellerLynn 2008) summarizes the findings of that meeting.

GRI GIS Data

Following the scoping meeting, the GRI team compiled the GRI GIS data for Pinnacles National Park. The data was compiled by the GRI in 2010 and updated in 2022. The GRI GIS data may be updated again if new, more accurate geologic maps become available or if software advances require an update to the digital format. These data are digital geologic maps and are the principal deliverable of the GRI. A geologic map is the fundamental tool for depicting the geology of an area. The GRI team did not conduct original geologic mapping but compiled existing geologic information (i.e., paper maps and/or digital data) into the GRI GIS data (fig. 1). Scoping participants and the GRI team identified the best available source maps based on coverage (area mapped), map scale, date of mapping, and compatibility of the mapping to the current geologic interpretation of an area. The GRI team may compile multiple source maps to cover a park boundary or provide a greater extent as needed for resource management.

The GRI GIS data for Pinnacles National Park was compiled from the following source maps:

- Geologic map of Pinnacles Volcanic Formation, California in Geology of the Pinnacles Volcanic Formation and the Neenach Volcanic Formation and their bearing on the San Andreas Fault problem (Matthews 1973)
- Geologic Map of the Monterey 30' x 60' quadrangle and adjacent areas, California (Wagner et al. 2002)
- Geologic Map of the Point Sur 30' x 60' quadrangle, California (Rosenberg and Wills 2016).

Two GRI GIS data sets were prepared from these source maps; a detailed map of the immediate area of the Pinnacles Volcanic Formation at 1:24,000 scale (identified as "PIVF" in the digital files) using only data from Matthews (1973), and a broader map of the park and surrounding regions at 1:100,000 scale using data from Wagner et al. (2002) and Rosenberg and Wills (2016) (identified as "PINN" in the digital files). The Rosenberg and Wills (2016) map incorporated much of Matthews (1973) map (see fig. 1) and updated the naming of units to modern conventions, specifically replacing the obsolete "Tertiary" with the respective epochs. The regional dataset (PINN) is the primary GRI GIS data referenced in this report, unless otherwise specified.

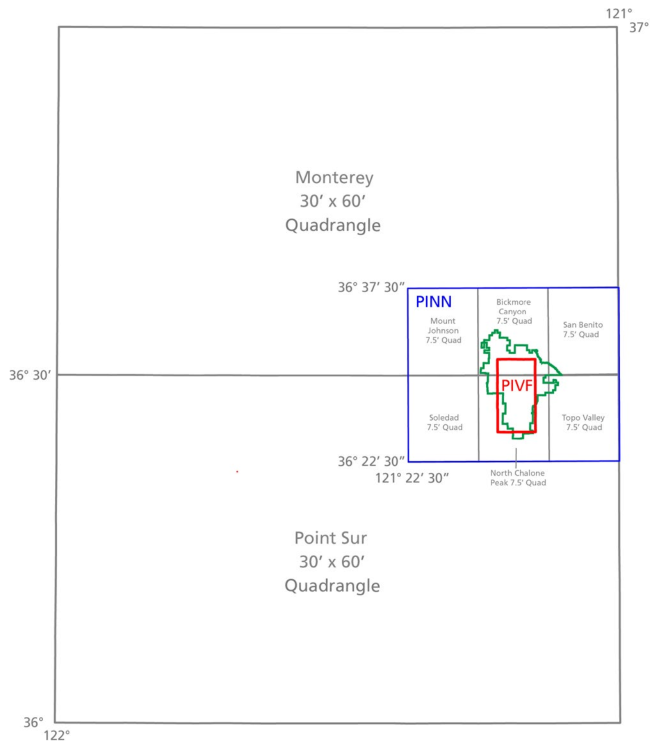

Figure 1. Index map of GRI GIS data.
This map shows the 7.5-minute quadrangles included in the GRI GIS data. The PINN dataset at 1:100,000 scale is compiled from the regional-scale 30′x60′ maps completed by the California Geological Survey, including the Monterey Quadrangle (Wagner et al. 2002) and the Point Sur Quadrangle (Rosenberg and Wills 2016). The PINN dataset, outlined in blue, uses three 7.5-minute quadrangles from each of these: the Mount Johnson, Bickmore Canyon, and San Benito quadrangles from Monterey; and the Soledad, North Chalone, and Topo Valley quadrangles from Point Sur. The PIVF dataset at 1:24,000 scale is a detailed map of the Pinnacles Volcanic Formation from Matthews (1973); the extent is outlined in red. NPS park boundary is in green. Graphic by Lucas Chappell (Colorado State University).

GRI Poster

A "GRI poster" of the 1:100,000 scale GRI GIS PINN data is the primary figure referenced throughout this GRI report. The poster is available on the "Geologic Resources Inventory—Products" website and through the NPS Integrated Resource Management Applications (IRMA) portal (see "Access to GRI Products"). The poster shows the GRI GIS data draped over a shaded relief image of the park and surrounding area. The poster is not a substitute for the GIS data but is supplied as a convenient tool for office and field use. Not all GIS feature classes are included on the poster (table 1). Geographic information, such as selected park, transportation, and hydrologic features, has been added to the poster. Shaded relief imagery and added geographic information are not included in the GRI GIS data but are available online from a variety of sources.

The colors on a geologic map delineate the rocks or deposits and their ages. On the GRI poster for Pinnacles National Park, blue, green, pink, and purple colors represent the oldest rocks, which are from the Paleozoic and Mesozoic Eras and are part of the granitic and metamorphic basement rock and overlying Mesozoic sedimentary rocks; brown, orange, and red colors represent sedimentary and volcanic rocks of the Paleogene and Neogene Periods (formerly Tertiary Period), including the Pinnacles Volcanic Formation; and yellow and light gray represent the youngest units, surficial deposits of the Quaternary Period, including the youngest unit which is made up of channel deposits from active creeks and streams. In addition to color, "map unit symbols" identify rocks on geologic maps. Usually, a map unit symbol consists of one or more uppercase letters indicating age (e.g., **K** for Cretaceous and **Ml** for Miocene) and lowercase letters indicating the rock formation's name or the type of deposit (e.g., **Kgdg** for the Cretaceous-age granodiorite of Gloria Road). Because of differences in geologic unit identifications between the source maps, some seemingly continuous units are labeled differently across quadrangle boundaries (e.g., **Kgdg** and **Ka**; see GRI poster). Other symbols on geologic maps depict the contacts between map units or structures such as faults or folds. Some map units, such as landslide deposits, delineate locations of past geologic hazards, which may be susceptible to future activity. Geologic maps also may show human-made features, such as roads and buildings.

Table 1. GRI GIS data layers for Pinnacles National Park (PINN).

PINN dataset only includes landslide direction arrows in the Monterey Quadrangle, i.e., the northern half of the map.

Data Layer	On Poster?
Geologic Attitude and Observation Points	No
Geologic Contacts	Yes
Geologic Units	Yes
Faults	Yes
Landslide Direction Arrows	Yes
Cross Section Lines	No
Mine Point Features	No

GRI Report

On 25 January 2018, the GRI team hosted a follow-up conference call for park staff and interested geologic experts. The call provided an opportunity to get back in touch with park staff, introduce "new" (since the 2007 scoping meeting) staff to the GRI process, and update the list of geologic features, processes, and resource management issues for inclusion in the final GRI report.

This report is a culmination of the GRI process. It synthesizes discussions from the scoping meeting in 2007, the follow-up conference call in 2018, and additional geologic research. The selection of geologic features was guided by the previously completed GRI GIS data, and writing reflects the data and interpretation of the source map authors. Information from the Pinnacles National Park foundation document (NPS 2015) was also included as it was applicable to the park's geologic resources and resource management. The GRI GIS data is linked to the geologic features and processes discussed in the report using map unit symbols (see the "GRI Poster" section).

Acknowledgements

The GRI team thanks the participants of the 2007 scoping meeting and 2018 follow-up conference call for their assistance in this inventory. The lists of participants (below) reflect the names and affiliations of these participants at the time of the meeting and call. Because the GRI team does not conduct original geologic mapping, we are particularly thankful for the California Geological Survey maps and Vince Matthew's work while at the University of California at Santa Cruz. This report and accompanying GIS data could not have been completed without them. Many thanks to Tim Connors, Jack Wood, Pat Seiser, Forrest Smith, and Kyle Hinds of the NPS Geologic Resources Division for their review of this report. Thanks to Trista Thornberry-Ehrlich (Colorado State University) for producing many of the figures in this report.

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GRI Map Poster Design

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Geologic Heritage of Pinnacles National Park

The geologic features, landforms, landscapes, and stories of Pinnacles National Park are an important part of the local and national heritage, from our collective understanding of global plate tectonics to the legislative history that preserves the area. This chapter highlights the significant geologic heritage of Pinnacles National Park and draws connections among the park's geologic resources and other park resources and stories.

Geologic Heritage (or "geoheritage") encompasses the significant geologic features, landforms, and landscapes characteristic of our Nation which are preserved for the full range of values that society places on them, including scientific, aesthetic, cultural, ecosystem, educational, recreational, tourism, and other values. The NPS also identifies geologic heritage aspects of museum collections, soils, and scientific data sets.

The park contains some of the starkest evidence for the motion of tectonic plates, both in the past and in the present; a rare and extensive assemblage of talus caves; and may represent the maximum displacement anywhere along the fault (Matthews 1976). These features, which cannot be found anywhere but in Pinnacles National Park, are globally significant in our modern understanding of geology and contain every geoheritage value listed above. These and additional geoheritage resources are described in the "Geoheritage Values of Park Resources" section of this chapter.

In 2015, the National Park Service's Geologic Resources Division staff in cooperation with the American Geosciences Institute published a booklet—*America's Geologic Heritage: An Invitation to Leadership* (National Park Service and America's Geosciences Institute 2015)— introducing the American experience with geoheritage, geodiversity, and geoconservation. This publication introduces key principles and concepts of America's geoheritage which are the focus of ongoing collaboration and cooperation on geologic conservation in the United States.

Park Background and Establishment

In 1906 President Theodore Roosevelt designated 14,080 acres of land as Pinnacles National Forest Reserve. Two years later, he designated 2,080 acres within the reserve as Pinnacles National Monument to preserve and protect the remnants of ancient volcanic processes that formed a portion of the Gabilan Mountain Range. Over the next hundred years various federal authorities added land to the monument and designated a portion as wilderness. The monument was redesignated Pinnacles National Park in 2013 by Congress with the stated purpose of protecting "…the Pinnacles Volcanic Formation, talus caves, associated lands, and ecosystems for their scientific, educational and cultural values…" Today the park consists of more than 27,000 acres (approximately 65% of which is designated as the Hain Wilderness).

Pinnacles National Park is in central California between the towns of Soledad and Paicines, approximately 80 miles (130 km) southeast of San Francisco and 40 mi (65 km) inland of the Pacific Ocean. The park has an east and west entrance, however, only hiking trails connect the east and west sides of the park (fig. 2; NPS 2015). The shortest route between entrances by vehicle is outside of the park through the town of King City on US Highway 101. Both entrances are open year-round. Currently and historically, the east side receives higher visitation and provides more visitor services (NPS 2015). In 2020, the park received 165,740 visitors (Ziesler and Spalding 2021). That number was down from previous years, likely a result of the global coronavirus pandemic.

The park is in a pocket of weathered volcanic rocks at the southern end of the predominantly granitic (non-volcanic) Gabilan Range, part of the northwest-trending valleys and ridges that make up the California Coast Ranges section of the larger Pacific Border Physiographic Province (fig. 3). The park terrain is dissected with canyons and the volcanic ridges typically stand over 1,000 ft (300 m) above the valley floors. The Salinas Valley, west of the park, contains some of the richest farmland in the world (Rosenberg and Wills 2016).

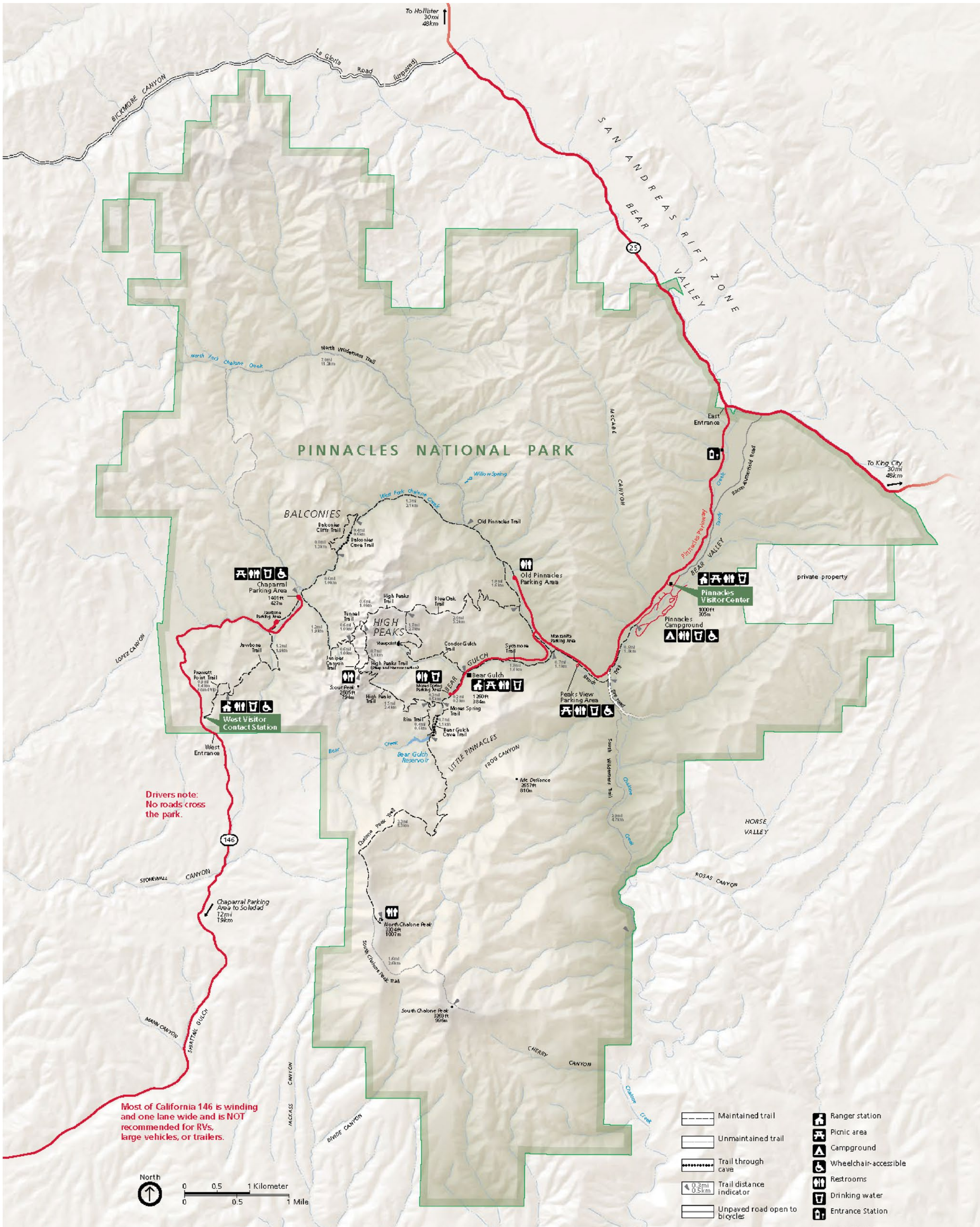

Figure 2. Map of Pinnacles National Park.
The primary access points to the park are on East Entrance Road on the east (Paicines) and California State Route 146 on the west (Soledad) side of the park. These roads, however, do not connect the two sides, nor does any other road within the park (NPS 2015). National Park Service map, available at www.nps.gov/carto.

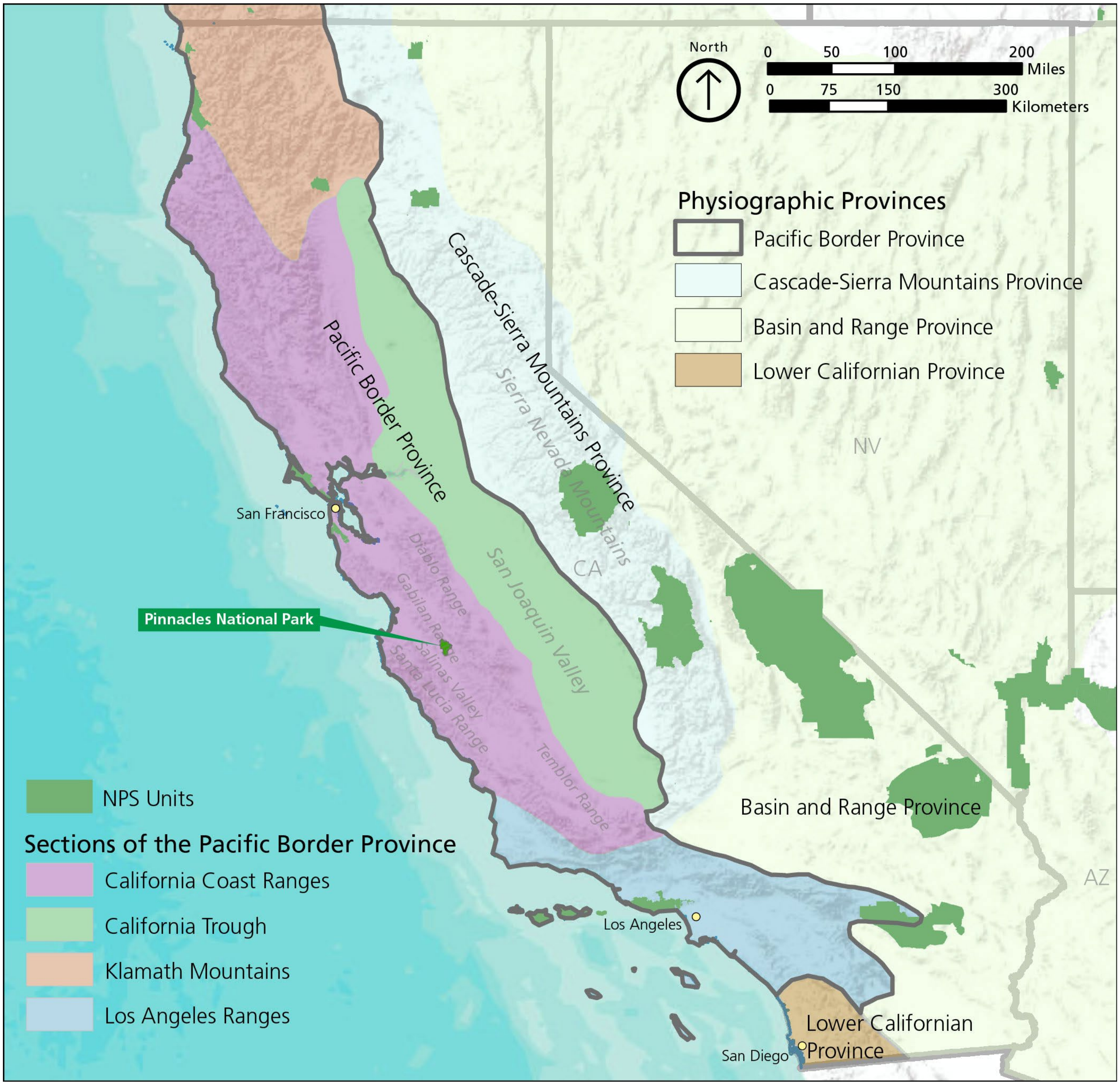

Figure 3. Physiographic Provinces of California.
The park is in the California Coast Ranges section, one of four sections of the Pacific Border Province. The California Coast Ranges section is characterized by a mixture of sea floor sedimentary rocks with igneous intrusions formed during the Paleogene and Neogene (formerly Tertiary), Cretaceous, and Jurassic Periods. The section is bordered to the north by the Klamath Mountains section, to the east by the California Trough section, to the south by the Los Angeles Ranges section, and to the west by the Pacific Ocean. The park landscape includes rocky crags, spires, and the namesake conspicuous pinnacles. Map graphic by Rebecca Port (National Park Service) and Michael Barthelmes (Colorado State University) using information from the California Geological Survey (2019).

Geologic Setting

This summary of the park's geologic setting provides a framework from which to appreciate the geologic heritage features in the park. A more detailed "play-by-play" of these events is in the "Geologic History" chapter of this report.

All landscapes are a result of geologic processes, but few are as striking in their geologic history as that of Pinnacles National Park. The regional landscape of parallel, northwest-trending ridges and valleys is a result of tectonic activity (e.g., earthquakes, volcanoes, mountain building) occurring at plate boundaries. Movement along faults and folds (that also trend northwest) formed the Santa Lucia Range, Sierra de Salinas, Gabilan Range, and the Diablo Range (Rosenberg and Wills 2016; Page et al. 1998). A tectonic block is a land mass between parallel faults which moves more or less as a cohesive unit. The park is on the Salinian tectonic block between the San Andreas and San Gregorio fault zones (fig. 4). The Salinian block is made up of metamorphosed sedimentary and igneous rocks.

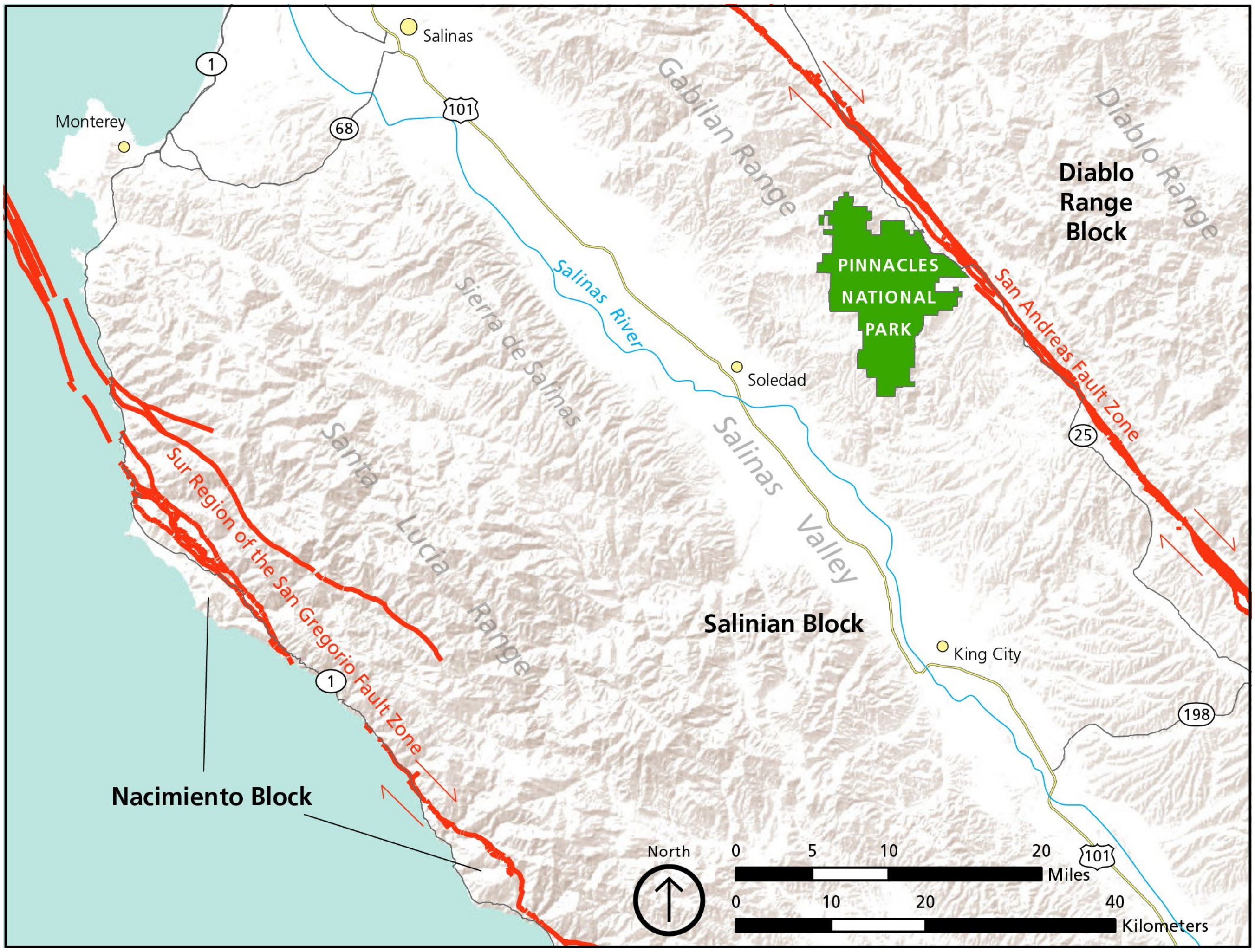

Figure 4. Map of tectonic blocks and faults around Pinnacles National Park.
The Salinian block is a northward-transported tectonic block bounded to the east by the San Andreas Fault and to the west by the Sur-Nacimiento and San Gregorio faults (Rosenberg and Wills 2016). Arrows indicate direction of relative lateral motion across the fault planes. Graphic by Rebecca Port (National Park Service) after Rosenberg and Wills (2016, Figure 2), with faults from USGS Quaternary faults database (https://www.usgs.gov/programs/earthquake-hazards/faults) and base map from Esri.

The volcanic rocks that characterize the park formed around 30 million years ago when the Farallon tectonic plate, composed of dense oceanic crust, subducted beneath the thicker and relatively buoyant continental crust of western North America. As the down going slab of crust subducted along with considerable amounts of seawater, it began to melt. The molten portion rose within the overlying continental crust to be erupted onto the granitic land surface as lava flows and layers of volcanic ash making up the Pinnacles-Neenach volcanic field. Eventually, the entirety of the Farallon oceanic plate at this latitude was consumed, causing the western boundary of North America to contact the north moving Pacific oceanic plate. This changed the type of plate boundary in this location from convergent (collision) to transform (sliding past each other laterally) (Atwater 1970; Page and Wahrhaftig 1989). As the remaining downgoing slab of crust was subducted along with considerable amounts of seawater, it began to melt, and the molten portion rose to be erupted onto a land surface of granitic rock as lava flows and layers of volcanic ash making up the Pinnacles-Neenach volcanic field. This new plate boundary, which would become the well-known San Andreas Fault system, is where relative lateral motion has been occurring since.

About 12–14 million years ago, the San Andreas Fault split the Pinnacles-Neenach volcanic field into two parts, transporting the Pinnacles portion that would become the park nearly 200 mi (320 km) north. During this movement, a graben, or down-dropped fault block, formed along the east margin of the Salinian block where regional motion along the San Andreas was partially taken up by the local Pinnacles and Chalone Creek faults. At this time the coastline was much farther inland than it is today. The down-dropped graben therefore caused part of the Pinnacles Volcanic Formation to become submerged, allowing marine sediments to deposit on top of the volcanic units thereby protecting the formation from erosion. West of the graben, the volcanic units uplifted and eroded, exposing the granitic bedrock and volcanic dikes—the "plumbing" of the once overlying volcanoes.

Around 3 million years ago, broad uplift of the Gabilan Range brought the previously submerged part of the Pinnacles Volcanic Formation above sea level. The power of wind and water began to erode the landscape into the dramatic spires, cliffs, and ledges we see today (Howard 1979). This erosion has continued into the present day as motion along the San Andreas Fault causes the Gabilan Range to continue to uplift, resulting in the formation of talus caves, as well as stream and landslide deposits in valleys.

Geoheritage Values of Park Resources

This section identifies the most significant geologic resources in the park and describes their value in terms of America's geoheritage. See "Additional References, Resources, and Websites" for more information on geologic heritage. The National Park System is a celebrated part of America's natural and cultural heritage. Although park units are not currently established specifically for "geoheritage" values, the foundation document for Pinnacles National Park (NPS 2015) contains a list of "fundamental resources and values" (FRVs) which are those features, systems, processes, experiences, stories, scenes, sounds, smells, or other attributes determined to warrant primary consideration during planning and management. Those FRVs with geologic components can be considered a part of America's geoheritage. Geologic FRVs include:

- Landforms and Geologic Faults Reflecting Past and Present Tectonic Forces
- Scenic Views and Wild Character
- Talus Caves
- Opportunities for Research and Study
- Native Species and Ecological Processes

The foundation document (NPS 2015) also identifies "interpretative themes," or the key stories or concepts that visitors should understand after visiting a park, which reflect the park purpose, significance, resources, and values. These themes help explain why a park story is relevant to people who may otherwise be unaware of connections that they have to an event, time, or place associated with the park. As with FRVs, those interpretive themes that are connected to geology have a geoheritage value as they connect the individual to the larger geologic story. Geologic interpretive themes include:

- Over millions of years, the power of volcanism, erosion, and plate tectonics created and transformed the Pinnacles Volcanic Field into the dramatic canyons, monoliths, and rock spires seen today. The 200 mile-offset (320 km) of the Pinnacles Volcanics from the Neenach Volcanics provides key evidence for the theory of plate tectonics.
- The enclosed dark spaces of Pinnacles' rare and extensive assemblage of talus caves, formed by massive rocks falling into narrow canyons, offer shelter, create habitat for bats and other specialized cave species, inspire legends, and encourage exploration and adventure.

In the same way that a visitor may feel inspired and motivated by understanding the cultural or natural heritage of a park, interpretive themes that connect the visitor to geologic FRVs are an invitation to leadership, creating a transformative understanding and sense of ownership of the visitor's own geoheritage.

Landforms and Geologic Faults Reflecting Past and Present Tectonic Forces

Naturalists and philosophers had observed oddities and incongruities about the physical character of the earth for hundreds and thousands of years. Fossilized fish appearing at mountainous elevations, volcanic eruptions and earthquakes, and a puzzle-like matching of coastlines separated by oceans led to early geologists suggesting that the continents "drifted" and that violent catastrophes occasionally reshaped the land. Not until the mid-20th century did scientists identify symmetrical spreading patterns in the seafloor and propose the theory of Plate Tectonics. If evolution is the basis of the modern synthesis in biology, then plate tectonics is the same for geology, providing a mechanism for much of the previously unexplained geologic phenomena. In the scientific process, the acceptance of a theory is increased with more supporting evidence. Pinnacles National Park provides some of the starkest evidence for the motion of tectonic plates, both in the past and in the present.

The Pinnacles-Neenach correlation refers to the proposed original alignment of rocks in both the Pinnacles and Neenach volcanic formations based on nearly identical visible and chemical characteristics, and stratigraphic (layered) order. Today these formations are separated by nearly 200 mi (320 km). This is the most conclusive evidence of large-scale lateral displacement along the San Andreas Fault in central California and may represent the maximum displacement anywhere along the fault (Matthews 1976). It is common knowledge today that the fault is moving laterally but proving that was somewhat difficult. The Pinnacles-Neenach correlation was perfect for such a task because (1) the rocks are adjacent to the fault, (2) they can be dated radiometrically to prove they are the same age, and (3) they contain a nearly identical sequence of rocks (rather than just one rock type) (Matthews 1976).

The towering pinnacles of rock, the namesake of the park, are all that remains of part of an ancient volcanic field. They are the eroded remnants of lava flows and pyroclastic material erupted roughly 23 million years ago. Over time, weathering and erosion carved into these layers of rock and sculpted the pinnacles, crags, and spires visible today (see "Cliffs and Spires" in "Pinnacles Volcanic Formation" section).

The volcanism that created the Pinnacles and Neenach volcanic features was the result of tectonic motion. The local switch from a subduction zone to a transform plate boundary created a mechanism for continental crust to partially melt and erupt (see "Development of the San Andreas Fault System" in the "Cenozoic Era" section). The later separation of those volcanic formations by 200 mi (320 km), and the folding and faulting of the volcanic and sedimentary rocks, is a result of the continued relative lateral motion of tectonic plates. The ongoing weathering and erosion of the volcanic rocks into the distinctive landforms of today is a result of the uplift driven by tectonic forces. Understanding the geologic history of the park and the geologic features, including the San Andreas Fault system, can contribute to an understanding of not only the geologic history of California and western North America but to the global process of plate tectonics which shapes and arranges Earth's continents (see "Geologic Features and Processes").

Scenic Views and Wild Character

The striking appearance of the pinnacles rocks and the surrounding geologic landscape provide dramatic views for visitors. Beyond these viewsheds, the park, 65% of which is dedicated as the Hain Wilderness, is celebrated for its natural soundscapes, dark night skies, Class 1 air quality, natural smells, and natural systems. All these features provide both inspiration and challenge for visitors seeking primitive recreation and solitude in natural settings. The high cliffs, hard rocks, and scenic views make the park a popular destination for rock climbing, with more than 900 climbing routes both inside and outside the wilderness and in the front country, as well as backcountry areas (NPS 2015).

Talus Caves

Many geoheritage sites are identified on the basis of their superlatives; the tallest, the longest, the deepest, et cetera. Pinnacles National Park contains the most extensive assemblage of accessible, rare talus caves within the National Park System (NPS 2015). Unlike the majority of cave systems managed by the National Park Service which form through karst processes or dissolution, talus caves exist in the open spaces among large rocks and boulders at the bases of cliffs or in narrow canyons.

Deep, narrow gorges and shear fractures lined by towering rock pinnacles set the stage for talus cave formation. An active weathering regime combined with the seismicity of an active fault zone causes boulders to loosen from the shear rock walls, topple, and wedge themselves in narrow gorges and fractures thereby creating the ceiling of a network of talus caves.

In addition to attracting bats and other cave dependent species, the talus caves entice park visitors. The caves have a rich human, as well as geologic, history. In the 1930s, the Civilian Conservation Corps (CCC) built trails through the caves, constructing bridges and stairways that allow navigation without ropes and ladders (KellerLynn 2008). These trails have endured many storms and travelers (fig. 5).

The caves are steeped in campfire legend as well. The most notable legend centers on the 19th century California bandido, Tiburcio Vasquez, whose notoriously violent career ended with his hanging in San Jose in 1875 (KellerLynn 2008). The local lore suggests that hidden treasure and robber's roosts await discovery in the caves, although the location of the cache appears to be purely speculative. See the "Talus Caves" section of the "Geologic Features and Processes" chapter for more information about the talus caves.

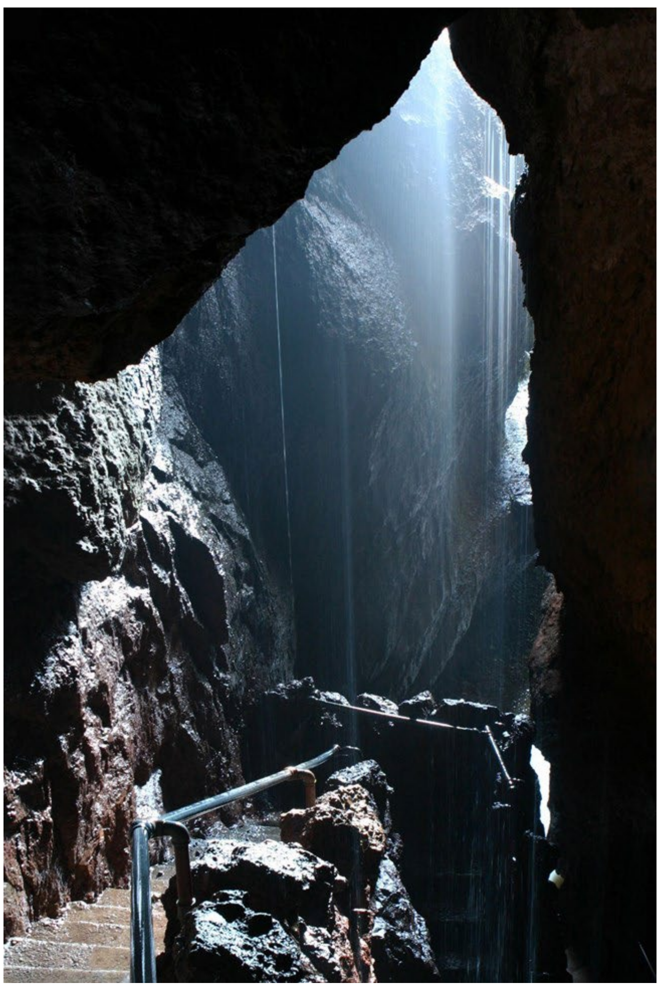

Figure 5. Bear Gulch talus cave.
The dramatic talus caves at Pinnacles National Park are a major draw for visitors, and access is made easier by the long-lasting trails, stairs, and railings constructed by the CCC in the 1930s. Photograph by Paul Johnson (National Park Service).

Opportunities for Research and Study

Geoheritage values emphasize scientific value, including furthering the cumulative geologic understanding of features and processes. The foundation document identifies pinnacles geology, plate tectonics, and talus caves as areas with continuing opportunities for research and study (NPS 2015). The public is often more interested in learning about park science if they understand how scientists work, and the processes behind discoveries. Locations of current and past research are opportunities to use the park as an "outdoor classroom," sharing not only the geologic story but also the story of the geologists' work.

At the scoping meeting (KellerLynn 2008), participants informally identified a paleontological investigation of marine and freshwater ostracodes and several other studies that could help refine the geologic story as it relates to the park. Other studies included analysis of the basement rocks to determine the start of fault movement, dating sedimentary rocks stratigraphically above the rocks exposed at the park, and conducting geologic mapping around Parkfield, CA to understand the Pinnacles-Neenach correlation story.

Geologic formations are commonly named after geographic features, including streams, rivers, or nearby cities where the unit is well exposed or first described. These scientifically important reference exposures are called "stratotypes." A type section is a geographically restricted stratotype and represents a measured and described reference exposure for a geologic unit (North America Commission on Stratigraphic Nomenclature 2021). During scoping Vince Matthews mentioned that he may have proposed a type section for the Pinnacles Volcanic Formation at the national monument; the National Geologic Map Database (2022) confirms this. The type section of the Pinnacles Volcanics, or Pinnacles Formation, is exposed along the High Peaks Trail, west of the Chalone Area. Vince Matthews documented the "Pinnacles Volcanic Formation" type locality in his PhD dissertation (Matthews 1973). Sims (1993) renamed the unit the "Pinnacles Volcanics" to conform to North American Stratigraphic Code and the California Geological Survey uses the name "Pinnacles Formation", however, the GRI GIS data continues to use "Pinnacles Volcanic Formation" (see GRI poster). The geologic type section inventory for the San Francisco Bay Area Inventory and Monitoring Network (Henderson et al. 2022) includes a list of stratotypes within 48 km (30 mi) of the park boundary. Contact the Geologic Resources Division for the spatial data of the stratotype locations (see "Guidance for Geologic Resource Management"). This information will be important in the event of park expansion.

Native Species and Ecological Processes

The park's dramatic and unique geologic landscape also provides habitat to a diverse assemblage of native plant and animal species. The shrubland plant community of chaparral, which covers most of the park, is found where the soil is coarse, gravelly, and humus poor (Keith 1991). Regionally, chaparral and oak woodland blanket the lower hillsides.

The rock pinnacles are a primary nesting area for prairie and peregrine falcons and provide nesting and roosting sites for golden eagles, American kestrels, swallows, California condors, and western mastiff bats which reside in crevices high in the cliffs. The park provides roosting habitat for bats in the form of rock outcroppings, caves, mines, mature oak woodlands, and riparian cottonwood stands (Heady 2005). Bats are economically and ecologically important animals providing ecosystem services such as pollination and insect predation (NPS 2006a). At least 14 species of bat were documented in the park, seven of which have special status (NPS 2006a, 2011).

The successes, or failures, of these species are dependent upon the integrity of the native habitats, and the interactions between the living and nonliving components. These include geologic features and processes discussed in this report, including erosion, flooding, fire, and tectonic activity. If visitors understand the role of geology in the wellbeing of the native species and ecological processes in the park they can have a better appreciation of the park role as a component of larger interdependent ecosystems.

Geologic History

This chapter describes the order of geologic events that formed the present landscape. Table 2 presents a complete time scale. Tables in each section show a segment of the geologic time scale with a chronology of geologic events that led to the park's present-day landscape. This story covers more than 66 million years.

Table 2. Geologic Eras and Periods.

The geologic time scale puts the divisions of geologic time in stratigraphic order, with the oldest divisions at the bottom and the youngest at the top. The Periods are further divided into Epochs; tables in this section of the report put the geologic units of the park into the context of these Periods. The oldest rocks mapped in the park are from the Cretaceous Period (K) of the Mesozoic Era.

*Precambrian is an informal name representing all geologic time before the Cambrian Period; it is not a formal era.

Era	Period	Millions of Years Ago
Cenozoic	Quaternary (Q)	2.6–today
	Neogene (N)	23.0–2.6
	Paleogene (PG)	66.0–23.0
Mesozoic	Cretaceous (K)	145.0–66.0
	Jurassic (J)	201.3–145.0
	Triassic (TR)	251.9–201.3
Paleozoic	Permian (P)	298.9–251.9
	Pennsylvanian (PN)	323.2–298.9
	Mississippian (M)	358.9–323.2
	Devonian (D)	419.2–358.9
	Silurian (S)	443.8–419.2
	Ordovician (O)	485.4–443.8
	Cambrian (C)	538.8–485.4
Precambrian*	n/a	~4,600–538.8

Mesozoic Era and Earlier (Before 66 million years ago)

The Mesozoic Era (252 million to 66 million years ago; table 2) comprises three periods, the Triassic (252 million to 201 million years ago), Jurassic (201 million to 145 million years ago), and Cretaceous (145 million to 66 million years ago). The Mesozoic is characterized by the existence of the supercontinent Pangea and its inhabitants, the dinosaurs. Although Earth looked little as it does today, the landmass of California was in the beginnings of being assembled. As Pangea was constructed (during the previous era, the Paleozoic Era) by the collision and accretion of smaller landmasses, western North America began to take shape. By 180 million years ago (the early Jurassic Period) the California landmass had grown through the accretion of island arcs to where the Sierra Nevada foothills are today, approximately 160 km (100 mi) east of the modern shoreline.

When an oceanic and continental tectonic plate converge, the thinner and denser oceanic plate sinks beneath the less dense continental plate at what is known as a subduction zone. Starting at the end of the Jurassic Period (around 150 million years ago; fig. 6), the subduction zone that formed the western margin of North America accumulated volumes of oceanic rock scraped off from the sinking Farallon Plate. These rocks make up most of what is known as the Franciscan Complex (Mulcahy et al. 2018, Wakabayashi 2017; fig. 7). Outcrops of the metamorphic rocks of the Franciscan Complex characterize much of the California coast and are included in the GRI GIS data (geologic map units **KJf**, **KJch**, **KJgs**, **KJum**, **KJbs**) although no Franciscan rocks are mapped in the park.

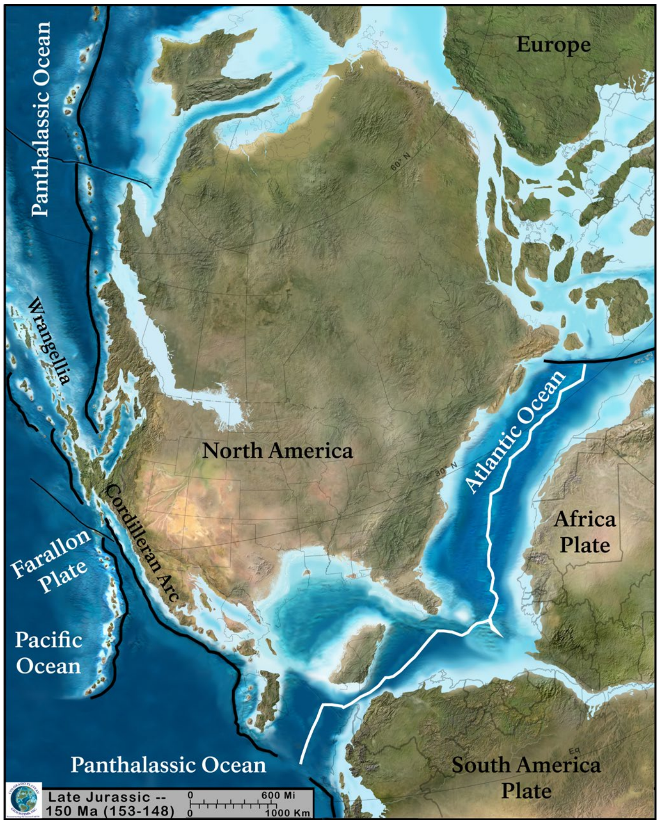

Figure 6. Paleogeographic map of North America during the Late Jurassic (150 million years ago). Even as the supercontinent Pangea rifted apart to form the Atlantic Ocean, oceanic plates collided with, and were subducted beneath the continent of North America's western margin. Island arcs and microcontinents were accreted to the western coast, building out what would become the modern landscape of California. By the late Jurassic Period, the California landmass had grown to where the Sierra Nevada foothills are today, approximately 160 km (100 mi) east of the modern shoreline. Paleogeographic map by Ron Blakey (North American Key Time Slices © 2013 Colorado Plateau Geosystems Inc., used under license).

The Cretaceous granitic basement rocks in the park (**Kgdg**, **Kqdj**, **Kgmb**) are plutonic igneous rocks that formed as magma cooled within the earth. They intruded into overlying Paleozoic carbonate sedimentary rocks (i.e., **PZls**), some of which were metamorphosed to marble and schist (**MZPZm**, **MZPZms**) when exposed to the extreme heat of the intrusive magma. These older metasedimentary rocks (sedimentary rocks that have been metamorphosed) appear in the GRI GIS data but are not mapped within the park. There are a few small outcrops of Paleozoic rock, too small to appear on maps of this scale (1:100,000), within the park (Russ Graymer, US Geological Survey, geologist, written communication, 29 March 2022). Table 3 is organized stratigraphically and describes the Mesozoic basement rocks that are mapped in the park.

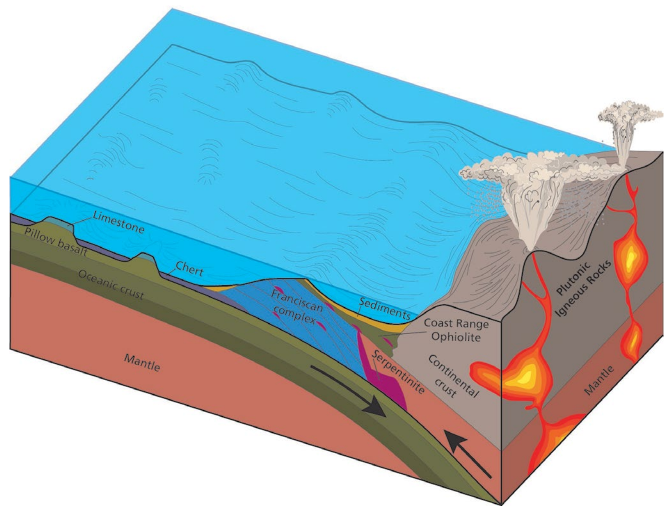

Figure 7. Diagram of the Mesozoic subduction system and emplacement of the Franciscan Complex.
During Cretaceous–Paleogene subduction, the oceanic Farallon plate (labeled oceanic crust on diagram) converged with and sank beneath the western edge of North America (labeled continental crust on diagram). The plutonic igneous rocks cooled to form the granitic basement rocks of the park that the Pinnacles Volcanic Formation was later erupted onto. Graphic by Trista Thornberry-Erhlich (Colorado State University) modified from Elder (2001, figure 3.3).

Table 3. Mesozoic rock units mapped within Pinnacles National Park.

The hills in the northwest and southeast areas of the park are underlain by Cretaceous-age granitic rocks that weather differently from the Cenozoic volcanic rocks in center of the park (see GRI poster). The Cretaceous is the final period of the Mesozoic, after the Triassic and Jurassic, and lasted from 145 million years ago to 66 million years ago. The Cretaceous rocks in the park formed between 91 million years ago and 83 million years ago.

Period colors are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps. Geologic map unit colors correspond to the colors used on the GRI poster. Detailed descriptions of these units are available as part of the GRI GIS data in the pinn_geology.pdf (see "GRI GIS Data" in the "GRI Products" section of this report).

Period	Geologic Map Unit (map symbol)	Description
Cretaceous (K)	Granodiorite of Gloria Road (**Kgdg**)	A light-colored, medium-grained granodiorite with biotite flecks. **Kgdg** is mapped in the northwestern extent of the park and is exposed along the North Wilderness Trail.
Cretaceous (K)	Quartz diorite-granodiorite of Johnson Canyon (**Kqdj**)	Dark-colored, medium-grained rock with abundant mafic minerals including euhedral hornblende. **Kgdj** is mapped in the far south of the park, and the western extent of the park where it is separated from the Pinnacles Volcanic Formation by the Pinnacles fault.
Cretaceous (K)	Quartz monzonite of Bickmore Canyon (**Kqmb**)	Light colored, medium-grained quartz monzonite with variable amounts of biotite and distinctive pink potassium-feldspar phenocrysts. Includes minor amounts of muscovite, green hornblende and magnetite. **Kgmb** is mapped extensively in the southeastern area of the park.
Jurassic (J)	n/a	Some Cretaceous-Jurassic units appear in the regional dataset (PINN), but none are mapped within the park boundary. Recent fieldwork by Russ Graymer (US Geological Survey) and Paul Johnson (National Park Service) suggests that an outcrop of Pinnacles Volcanic Formation dikes (**MIOLdi**) within the park has been misidentified and is actually Mesozoic marble (**MZPZm**). The outcrop occurs in the Prewett Point trail loop just north of the west entrance. It is conspicuous on the PINN map because it is mapped as a rounded feature in comparison to the linear units of **MIOLdi** around it (see GRI poster).
Triassic (TR)	n/a	No units from the Triassic exist in the GRI GIS data

Cenozoic Era (66 million years ago to present)

The Mesozoic Era ended with a bang as the dinosaurs, along with three quarters of life on Earth, became extinct in perhaps the best-known mass extinction event in Earth's history. During the Cenozoic Era (table 4), as the continents began to approach positions more recognizable today, a series of marine transgressions and regressions (rise and fall in sea level) combined with the down-dropping of tectonic blocks submerged parts of the Mesozoic rocks in the park and their intrusive igneous components and deposited sedimentary rocks upon them.

Uplift beginning during the Eocene Epoch (56 million to 34 million years ago) created a series of granitic islands along the California coast, separated by marine basins (Rosenberg and Wills 2016). Erosion of the granitic material above sea level, combined with marine deposition, created alternating layers of deep- and shallow-marine sediments. Although these sedimentary units inform the regional geologic history, and some appear in the GRI GIS data (e.g., **TKu**, **Ed**, **Ek**), none are mapped within the park. By the end of the Oligocene Epoch (23 million years ago), the area that is now the Gabilan Range had eroded down to its granitic roots (Howard 1979). It was onto these granitic rocks that the Pinnacles Volcanic Formation would erupt.

Table 4. The Cenozoic Era

The Cenozoic Era is broken into Periods and Epochs. The "T" in some map unit symbols (e.g. TKu, QTp) refers to the Tertiary Period, a now informal but still widely used term for the geologic period from 66 million to 2.58 million years ago. The Tertiary is now formally represented by the Paleogene (66 million to 23 million years ago) and Neogene (23 million to 2.58 million years ago) Periods. The Cenozoic rocks mapped within the park are described in tables in this section.

Period	Epoch	Millions of Years Ago
Quaternary (Q)	Holocene (H)	0.0117–today
	Pleistocene (PE)	2.6–0.0117
Neogene (N)	Pliocene (PL)	5.3–2.58
	Miocene (MI)	23.0–5.3
Paleogene (PG)	Oligocene (OL)	33.9–23.0
	Eocene (E)	56.0–33.9
	Paleocene (EP)	66.0–56.0

Development of the San Andreas Fault System

The San Andreas Fault system represents a transform plate boundary (lateral movement) between the Pacific and North American tectonic plates. The transform boundary replaced the convergent boundary between the Farallon and North American plates as the full width of the Farallon plate was locally consumed by subduction and the spreading ridge between the Farallon and Pacific plates came into the subduction zone. This intersection of the spreading ridge and subduction zone first occurred near modern-day Los Angeles about 28 million years ago (during the Oligocene Epoch); this area is known as the Mendocino triple junction because three tectonic plates—Pacific, Farallon, and North American—intersect (Port 2016; Atwater 1970; Atwater and Stock 1998; Page and Wahrhaftig 1989).

As subduction continued to consume the Farallon plate, the Mendocino triple junction migrated northward over millions of years, and the transform fault lengthened in its wake (fig. 8). The northward migration was also accompanied by episodic volcanism along "coastal" California (west of the modern San Andreas Fault, although east of the transform boundary at the time) as a trailing gap in the crust allowed mantle material to well up to the surface (Stanley et al. 2000). The Pinnacles-Neenach formation erupted during the second of three periods of transform margin volcanism identified by Stanley et al. (2000). Between 14 million and 12 million years ago the original transform fault was abandoned, and movement jumped eastward to be taken up by the many faults of the San Andreas Fault system.

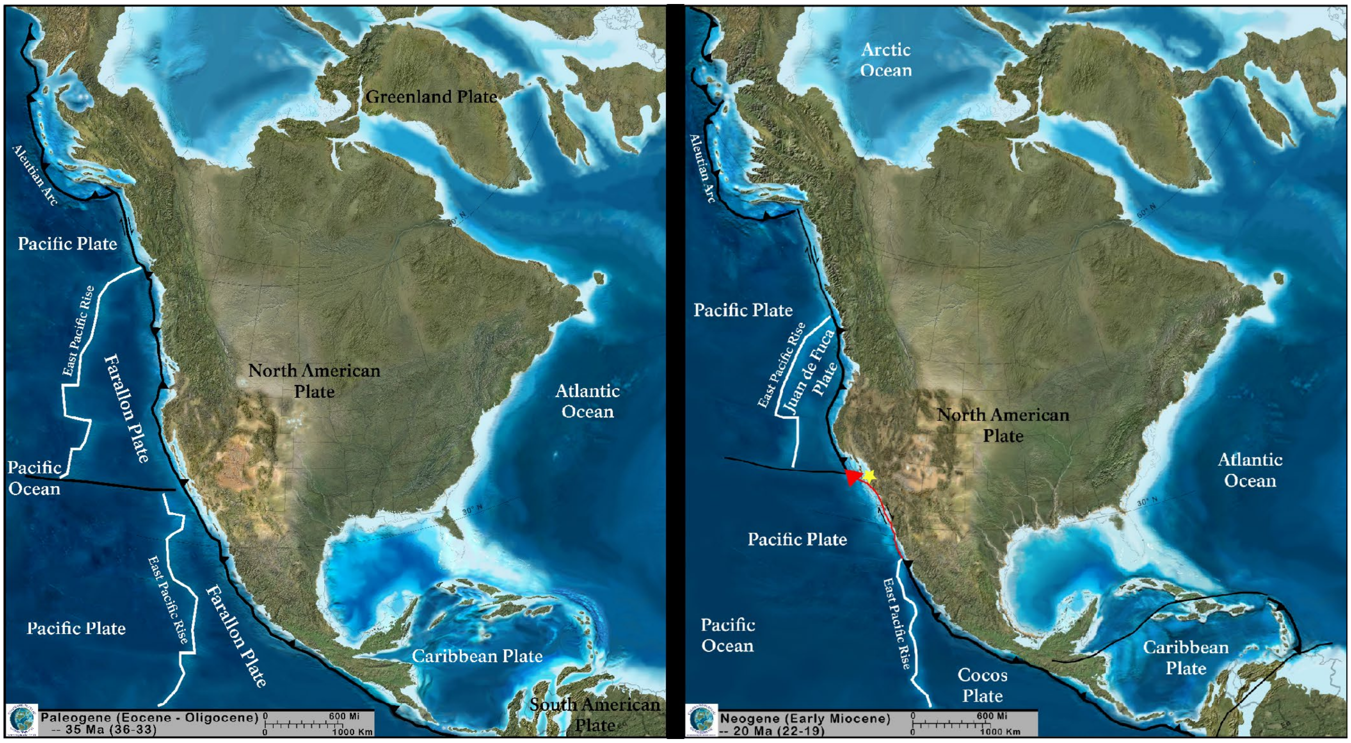

Figure 8. Paleogeographic maps of North America and the Mendocino Triple Junction. At 35 million years ago (left), marine and coastal marine sediments eroded from the granitic roots of the Sierra Arc mountains had deposited onto Cretaceous basement rock. The Farallon Plate was being consumed by subduction beneath North America. By the end of the Oligocene, the area of the Gabilan Range had eroded down to the granitic roots, onto which the Pinnacles-Neenach Formation would be erupted. At 20 million years ago (right), the Mendocino Triple Junction (red triangle) had formed where the Pacific Plate contacted the North American Plate and began migrating northward, extending the transform fault boundary in its wake. Between 24 million and 22 million years ago the Pinnacles-Neenach Formation (yellow star) erupted onto the Cretaceous granite. Paleogeographic map by Ron Blakey (North American Key Time Slices © 2013 Colorado Plateau Geosystems Inc., used under license), annotations by Michael Barthelmes (Colorado State University).

Pinnacles Volcanism

Geologists estimate that about 7 mi^3 (29 km^3) of volcanic material erupted from five main volcanic centers, although at least half of that is now lost to erosion (Alt and Hyndman 2000). Magma rose through fractures in the granitic basement rocks, forming dikes and sills (linear and planar intrusive formations; **MIOLdi**), and erupted onto the surface as lava flows, ash, and volcanic glass. The eruptions were often explosive, blasting lava, ash, and fragments of rock into the air and creating pyroclastic flows. Intense heat fused these elements together to create volcanic breccias.

Eruption of the Pinnacles Volcanic Formation took place during an episode of relatively intense volcanism between 24 million and 22 million years ago, over the Oligocene-Miocene boundary (fig. 9). Marine microfossils in only some of the Pinnacles Volcanic Formation rocks (e.g., ostracodes in **MIOLpbt**) indicate that those areas were submerged part of the time during its eruptive history (Matthews and Webb 1982).

Magma and lava cool to form rocks which are classified by their silica (silicon dioxide, SiO_2) content. Melts with low silica content, called "mafic" rocks for their high magnesium and iron (ferric) content, produce rocks like basalt that are denser and darker in color. The lava flows of Hawai'i are generally mafic. Felsic rocks, named for the common silicate mineral feldspar, form rocks of lighter colors like pink and white granites. The igneous rocks in the park are dominantly felsic rocks.

Igneous rocks are also classified by whether they cooled from a melt inside the earth (intrusive; magma) or on the surface (extrusive; lava). Rocks formed intrusively cool slowly and often form large crystals, whereas extrusive rocks cool quickly and are more likely to have air pockets and bubbles than crystals. The igneous rocks of the Pinnacles Volcanic Formation are extrusive; the Cretaceous basement rocks are intrsuive.

The silica content of a melt affects the way that it extrudes onto the surface. Increased silica makes a melt more viscous (thicker, and more resistant to flow). Mafic melts with low silica content can flow laterally for miles, like the Columbia River Basalt flows (see Graham 2019) or the volcanoes of Hawai'i (see Thornberry-Ehrlich 2009); felsic melts are more inclined to accumulate vertically like a thick porridge. This resistance also means that the vents through which the lava is erupting are prone to becoming blocked, resulting in pressure building up until lava is forced out in an explosive eruption. The Pinnacles Volcanic Formation likely erupted in this manner.

The extrusive rocks at the park range in silica content from andesite (less silica) to rhyolite (more silica). Most of the Pinnacles Volcanic Formation rocks are rhyolitic, the extrusive equivalent of granite. Rhyolite and other lava flows are interlayered with tuff, a rock formed from cemented volcanic ash; lahar (ash and other volcanic debris flow) deposits; and breccia, rock formed of cobblestone-sized angular blocks of rock fragments embedded in volcanic ash and glass welded together by the heat of a pyroclastic flow. Together, these rocks (table 5) form the Pinnacles Volcanic Formation (**MIOLp** units).

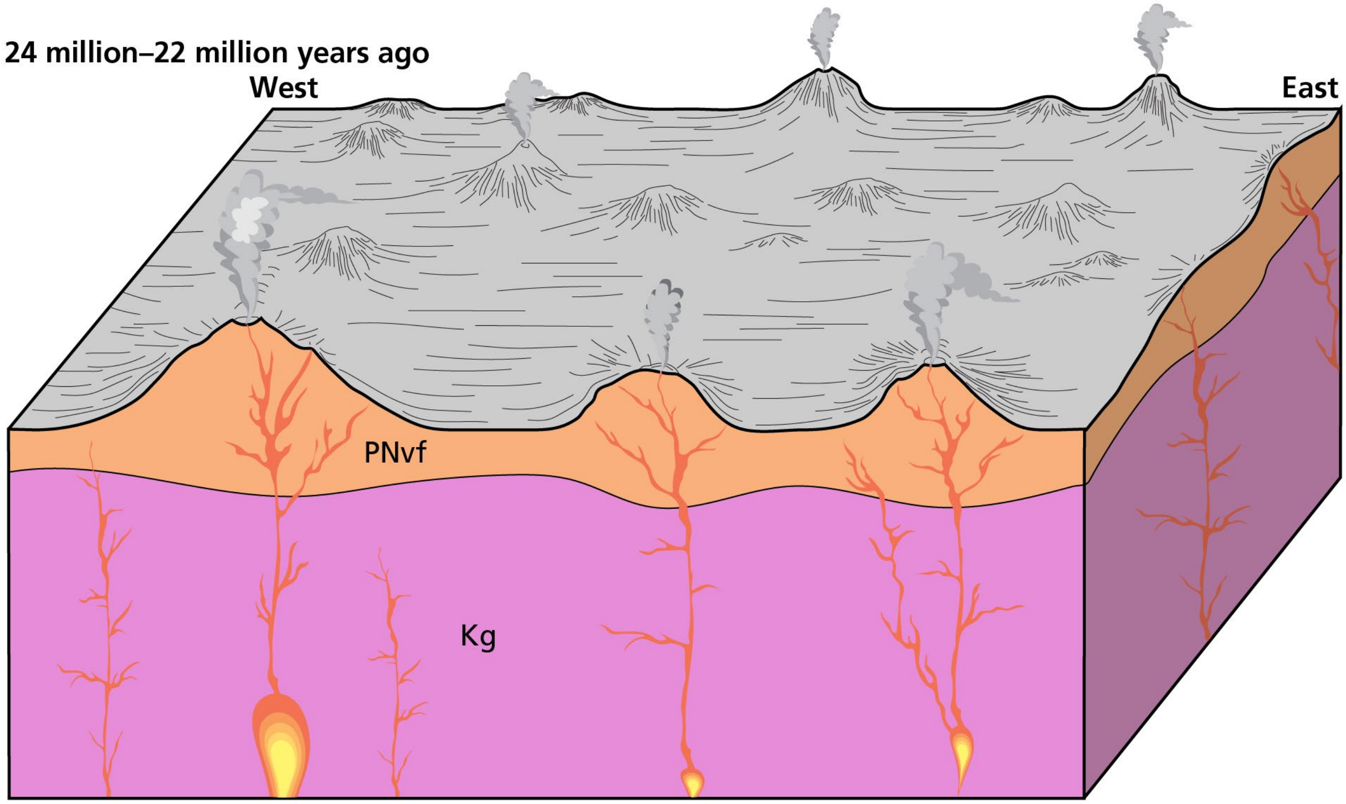

Figure 9. Diagram of the eruption of Pinnacles-Neenach volcanics.
Between 24 million and 22 million years ago, magma rose through fractures in the granitic basement rocks, forming dikes and sills, and erupted onto the surface as lava flows, ash, and volcanic glass. The eruptions were often explosive, blasting lava, ash, and fragments of rock into the air and creating pyroclastic flows. Intense heat fused these elements together to create volcanic breccias. Kg signifies generalized Cretaceous granite; PNvf signifies generalized Pinnacles-Neenach volcanics. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Table 5. Pinnacles Volcanic Formation rock units mapped in Pinnacles National Park.

The Pinnacles Volcanic Formation was erupted over the Oligocene-Miocene boundary, between about 24 million and 22 million years ago.

Geologic map unit colors correspond to the colors used on the GRI poster. Unit descriptions come from Matthews (1973) unless otherwise noted. Detailed descriptions of these units are available as part of the GRI GIS data in the pinn_geology.pdf (see "GRI GIS Data" in the "GRI Products" section of this report).

Geologic Map Unit (map symbol)	Description
Pinnacles Volcanic Formation (**MIOLpv**)	The Wagner et al. (2002) map of the Monterey 30′ x 60′ quadrangle does not differentiate between units of the Pinnacles Volcanic Formation; these units north of the quadrangle boundary are all grouped together as the unit **MIOLpv**. For a detailed view of the small section (see fig. 1) of the Pinnacles Volcanic Formation that is mapped by Wagner et al. (2002) as **MIOLpv**, see the Pinnacles Volcanic Formation (PIVF) GRI GIS dataset.
Pinnacles Volcanic Formation, Breccia Member, white aphanitic rhyolite flows (**MIOLpbr**)	Rhyolite flows of **MIOLpbr** are layered within the breccia and tuff unit (**MIOLpbb**) that dominates the western side of the Pinnacles Volcanic Formation. Mapped in some places as fault-bounded blocks within **MIOLpbb**.
Pinnacles Volcanic Formation, breccia and tuff (**MIOLpbb**)	Reddish brown breccia and tuff-breccia, includes lapilli-tuff and minor tuff. Layering defined by sparse erodible tuff layers within breccia. Thickness ranges from 500 to 800 m (1640 to 2625 ft) in the central Pinnacles area, where this unit forms the Balconies and High Peaks cliffs, and North Chalone Peak. Gradational contact with underlying tuff unit (**MIOLpbt**).
Pinnacles Volcanic Formation, Breccia Member, predominately tuff (**MIOLpbt**)	Thin, cream-colored beds of breccia, tuff-breccia, and lapilli tuff. Gradational contact with overlying breccia and tuff unit (**MIOLpbb**). Mapped as a thin band on the east side of **MIOLpbb** in and north of the Bear Gulch area.
Pinnacles Volcanic Formation, Porphyritic Rhyolite Member (**MIOLppr**)	Pale pink, porphyritic rhyolite. "Porphyritic" refers to an igneous rock with distinctly differently sized mineral grains, in this case large crystals of plagioclase, quartz, and biotite within a grayish pink to pale reddish groundmass. **MIOLppr** is mapped in small extents in the Bear Gulch area.
Pinnacles Volcanic Formation, Dacite Member (**MIOLpd**)	Gray, with yellow-green and pale red porphyritic dacite flows and breccia. Crops out in a discontinuous north-south belt with exposures at the intersection of the Old Pinnacles Trail and North Wilderness Trail, in Bear Gulch and the Little Pinnacles, and in Divide Canyon.
Pinnacles Volcanic Formation, Agglomerate Member (**MIOLpag**)	Large (<1 m [3 ft]) boulders of rhyolite, dacite, granitic rocks, pegmatite, and pumice-lapilli tuff at base of unit, with individual beds and overall unit fining upwards. Unit is 0 to 70 m (0 to 230 ft) thick. The large boulders suggest high-energy deposition, likely as lahars, or a debris flows of pyroclastic material, rocky debris, and water. Mapped in Bear Gulch and Little Pinnacles.

Table 5, continued. Pinnacles Volcanic Formation rock units mapped in Pinnacles National Park.

Geologic Map Unit (map symbol)	Description
Pinnacles Volcanic Formation, Andesite Member (**MIOLpa**)	Brown, black, and red andesite flows mapped in Bear Gulch, crossing High Peaks Trail, and immediately south of Old Pinnacles Trail/the West Fork Chalone Creek. The unit is glass in parts, and in parts brecciated and vesicular (containing air bubbles).
Pinnacles Volcanic Formation, Pumice Lapilli Tuff Member (**MIOLppl**)	White and greenish-gray thin beds consisting of pumice fragments and some clasts of rhyolite. Exposed in a thin band north of Bear Gulch, and extensively in fault-bounded blocks in the South Chalone Peak area where it forms resistant cliffs and ledges. 0 to 80 m (0 to 260 ft) thick.
Pinnacles Volcanic Formation, Rhyolite Member, massive rhyolite (**MIOLprm**)	Very light gray to pale red rhyolite that is the dominant unit between Mt. Defiance and South Chalone Peak.
Pinnacles Volcanic Formation, Rhyolite Member, perlite (**MIOLprp**)	Black to dusky green, flow-banded perlite (volcanic glass with high water content) that is interpreted to be the hydrated, chilled top of the flow banded rhyolite member (**MIOLprf**). Mapped in Cherry Canyon and surrounding area.
Pinnacles Volcanic Formation, Rhyolite Member, flow banded rhyolite (**MIOLprf**)	Pale reddish-purple, yellowish gray, or grayish red on fresh surfaces that weathers to a pale yellowish orange. Mapped in wide extents from the Old Pinnacles Trail down to the Cherry Canyon area, the unit is estimated to be 700 to 1,000 m (3,000 to 3,300 ft) thick.
Pinnacles Volcanic Formation, Rhyolite Member, vitric lapilli tuff (**MIOLprv**)	Black, perlitic tuff and gray pumiceous tuff that includes clasts of obsidian, pumice, and granitic rocks. Between 30 and 140 m (100 to 460 ft) thick, the unit is mapped as a thin band that borders the flow banded rhyolite (**MIOLprf**) to the east.
Pinnacles Volcanic Formation, dikes (**MIOLdi**)	Andesite, dacite, and rhyolite hypabyssal volcanics, mostly dikes, throughout Pinnacles Volcanic formation and including bodies mapped by Andrews (1936) and modified by Dibblee (1971) within the plutonic rocks (i.e., **Kgdj**, **Kqmb**) surrounding the Pinnacles volcanic center.

Miocene and Pliocene Epochs (23 million to 2.6 million years ago)

The volcanic activity that created the rocks of the Pinnacles Volcanic Formation occurred over the boundary of the late Oligocene and early Miocene (between 24 million and 22 million years ago). Beginning in the middle Miocene, the geologic story of the park involves lateral movement along the San Andreas Fault system, regional normal faulting associated with the Pinnacles and Chalone Creek faults, and sea level transgression and regression.

The northward migration of the Mendocino Triple Junction, and the lengthening transform fault boundary along the old subduction margin continued until the movement jumped eastward to the Pinnacles-Neenach Volcanic formation between 14 million and 12 million years ago (Atwater and Stock 1988) and split the formation in two. This marks the initiation of the San Andreas Fault system. The portion of the volcanic formation on the west side (Pinnacles) began to move northward relative to the eastern portion (Neenach), carried by the movement along the San Andreas Fault.

At this time the San Andreas Fault was a broad zone which included both the Pinnacles and Chalone Creek faults that run through the park (see "Faults and Folds"). Movement along the Pinnacles and Chalone Creek faults was normal (up-down) and created horst and graben topography of fault blocks thrust up or dropped down relative to each other; the westernmost block uplifted and the volcanic rocks were subjected to weathering and erosion. The eastern block dropped down and accumulated thick sediments eroded from the uplifted block. The center block—along with the core of the Pinnacles Volcanic Formation— remained at about the same level but was tilted down toward the northwest and received only a thin covering of sedimentary rocks (fig. 10).

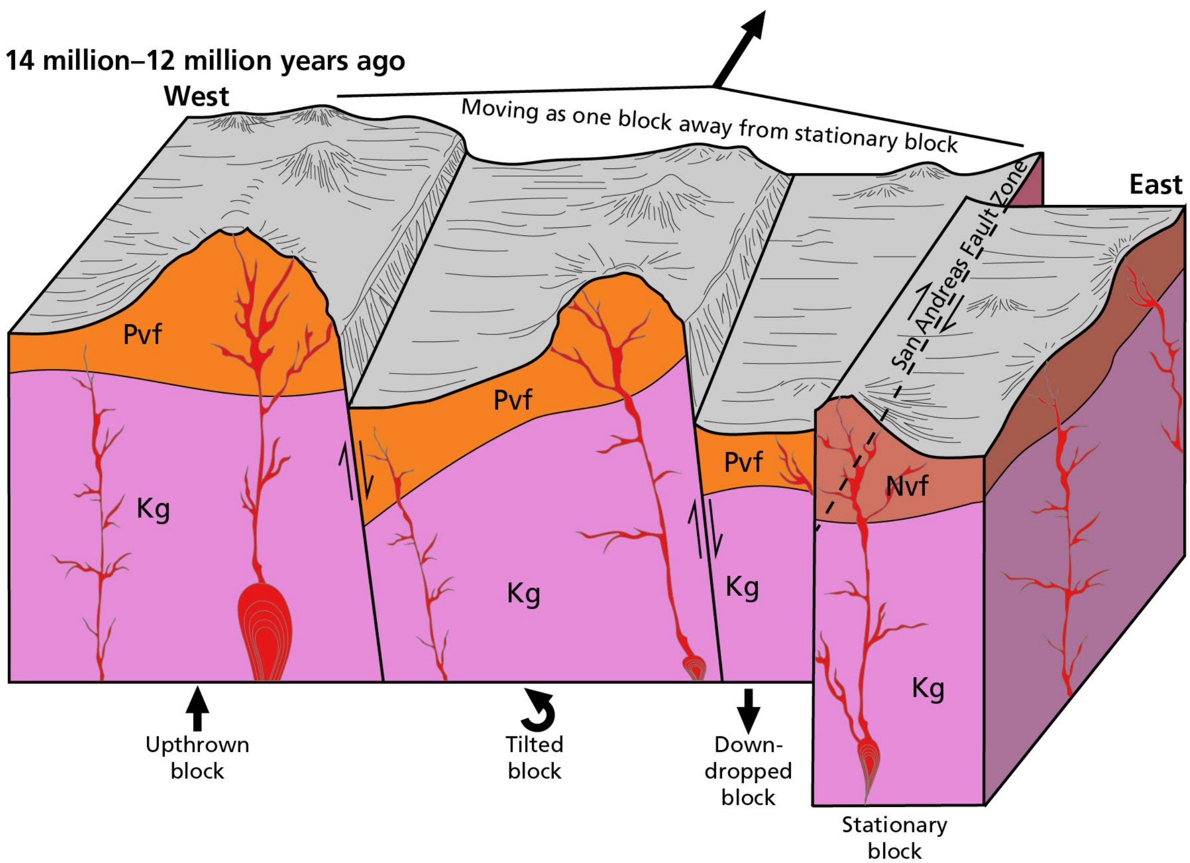

Figure 10. Diagram of Pinnacles-Neenach faulting.
The broad San Andreas Fault zone split the Pinnacles and Neenach volcanic rocks, towing the Pinnacles section northward. The area was also subjected to normal (up-down) faulting along the Pinnacles and Chalone Creek faults, breaking the Pinnacles volcanic rocks into three large blocks. The westernmost block was upthrust, the center block remained at the same relative elevation but was tilted down toward the northwest; and the eastern block dropped down. Kg signifies generalized Cretaceous granite; Pvf signifies Pinnacles Volcanic Formation; Nvf signifies Neenach volcanics; arrows indicate direction of fault movement. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

The erosion of the western block removed nearly all of the volcanic rock, exposing the granitic basement (**Kgdg**, **Kgdj**) and the "plumbing" of the volcanic field (**MIOLdi**, **MIOLpv**). Much of the eroded material was deposited as sedimentary rocks on the down-dropped eastern block, forming the Bickmore Canyon Arkose (**Mlbc**; fig. 11).

Some of the eroded material was carried even farther and deposited on the east side of the San Andreas Fault—the progress of the northward journey of the Pinnacles Volcanic Formation can be traced as sedimentary deposits east of the San Andreas Fault in the Temblor Range up to Lonoak, California (Russ Graymer, written communication, 29 March 2022).

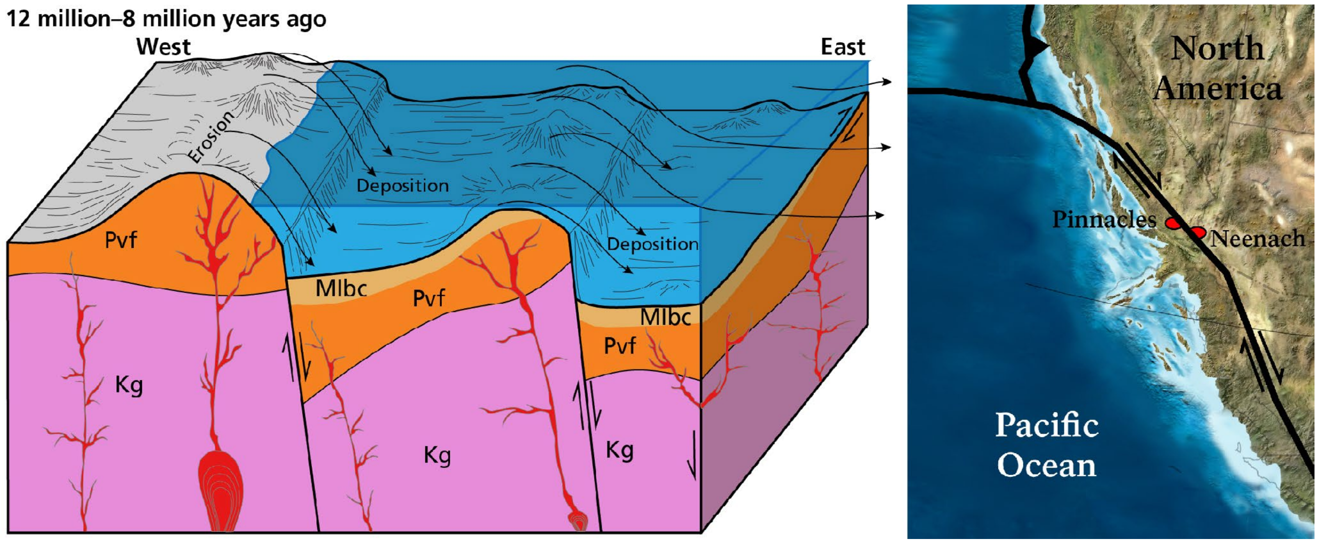

Figure 11. Diagram of erosion and submersion of the Pinnacles Volcanic Formation. Between 12 million and 8 million years ago, shallow water covered parts of the Pinnacles Volcanic Formation (left diagram). The exposed volcanics on the upthrust western block eroded and the sediments washed eastward into the basins to be deposited on top of the submerged blocks as the Bickmore Canyon Arkose (Mlbc). Some of these sediments washed all the way across the San Andreas Fault to be deposited along the Temblor Range in what is now southern California. The transform fault of the San Andreas Fault system (right) continues to separate the Pinnacles and Neenach volcanics. Kg signifies generalized Cretaceous granite; Pvf signifies Pinnacles Volcanic Formation; arrows indicate direction of fault movement. Block diagram by Trista Thornberry-Ehrlich (Colorado State University). Detail of paleogeographic map by Ron Blakey (North American Key Time Slices © 2013 Colorado Plateau Geosystems Inc., used under license), annotations by Michael Barthelmes (Colorado State University).

Around 8 million years ago, movement along the Chalone Creek and Pinnacles faults was waning. Deposition on the down-dropped eastern block transitioned from marine sediments to estuarine and non-marine sediments—a change reflected in the Bickmore Canyon Arkose (**Mlbc**). By about 6 million years ago (fig. 12), the shallow marine mudstones of the Pancho Rico Formation (**PLMlpo**) were being deposited upon the southern flank of the Gabilan Range. Although the base of this unit is cut by the Chalone Creek fault, the upper part is not (Russ Graymer, written communication, 29 March 2022), indicating that movement along the San Andreas Fault had shifted eastward.

The diminished elevation of the Pinnacles Volcanic Formation at the end of the Miocene and into the Pliocene is crucial to its story. While the uplifted rocks of California were being eroded—including the Neenach Volcanics to the south—parts of the Pinnacles Volcanic Formation were protected from erosion beneath a shallow sea and a thin cover of sedimentary rocks (e.g. **Mlbc**). Table 6 describes these and other Cenozoic sedimentary rock units mapped in the park.

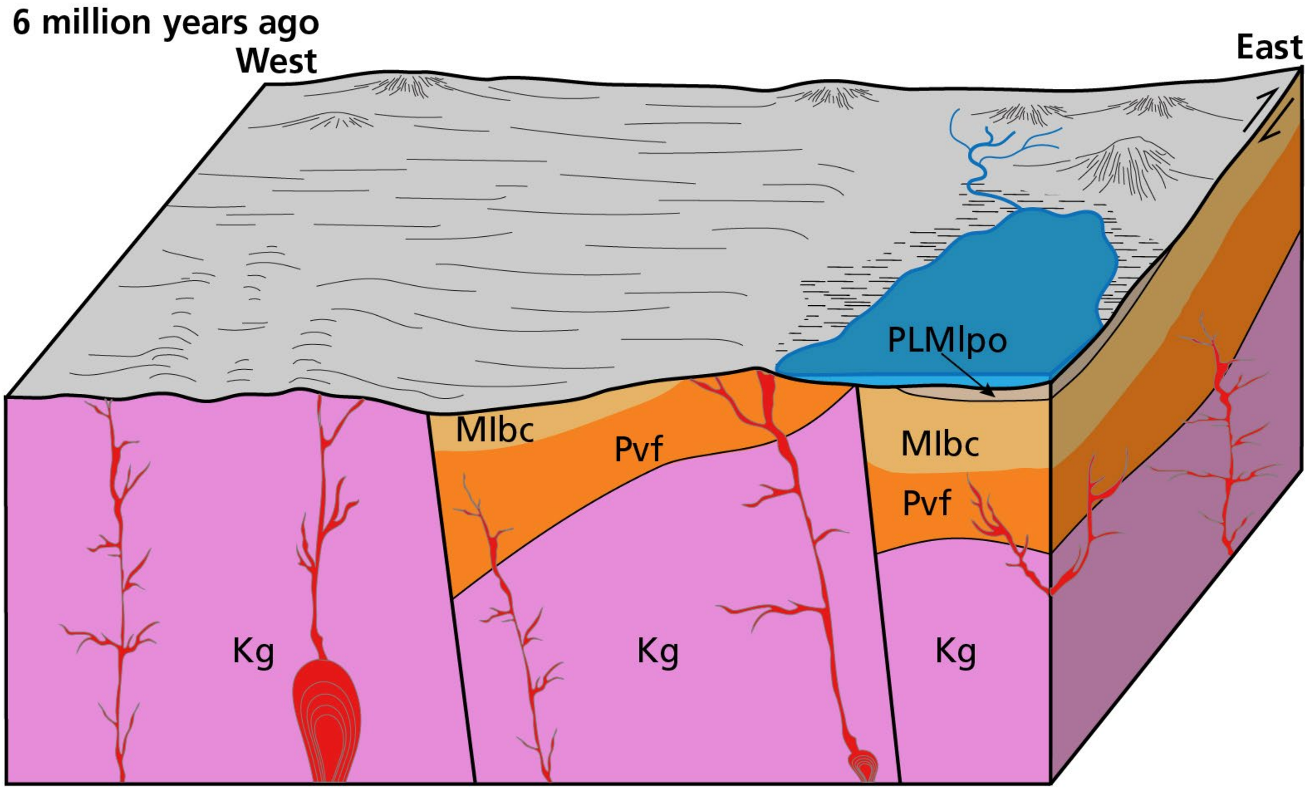

Figure 12. Diagram of Pancho Rico Formation deposition.
By 6 million years ago movement along the normal faults that run through the park had subsided. The volcanic rocks on the western block had eroded down to the Cretaceous granite and exposed the "plumbing" of the volcanoes. On the tilted center block, a thin layer of sediment (Mlbc) covered the "core" of the Pinnacles Volcanic Formation (Pvf). The down-dropped eastern block was covered by the thick Bickmore Canyon Arkose (Mlbc) which transitions upwards from marine-derived sediments into estuarine/non-marine sediments. The shallow marine mudstone of the Pancho Rico Formation (PLMlpo) was being deposited in basins along the southern flank of the Gabilan Range to the northwest. Kg signifies generalized Cretaceous granite; arrows indicate direction of fault movement. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Table 6. Cenozoic sedimentary rock units mapped within Pinnacles National Park.

Period and epoch colors are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps. Geologic map unit colors correspond to the colors used on the GRI poster. Unit descriptions are from Matthews (1973), Wagner et al. (2002), and Rosenberg and Wills (2016). Detailed descriptions of these units are available as part of the GRI GIS data in the pinn_geology.pdf (see "GRI GIS Data" in the "GRI Products" section of this report).

Period	Epoch	Geologic Map Unit (map symbol)	Description
Quaternary and Neogene	Pliocene and Pleistocene	Paso Robles Formation, undifferentiated (**QTp**)	Pebble conglomerate, akosic sandstone, and mudstone. Lack of marine fossils and resemblance to older alluvial deposits indicates non-marine fluvial and alluvial fan deposition. **QTp** is primarily mapped in small exposures at the south-westernmost extent of the park, along the Pinnacles fault.
Neogene	Miocene to Pliocene	Pancho Rico Formation, mudstone (**PLMIpo**)	Light brown marine siltstone that contains diatoms and locally common fish scale and bivalve fossils. **PLMIpo** is mapped in the eastern extent of the park, east of Grassy Canyon.
	Miocene	Bickmore Canyon Arkose (**MIbc**)	Pale brown to greenish gray coarse akosic (high in feldspar) gravel and conglomerate that includes blocks of granite and rocks of the Pinnacles Volcanic Formation. The lower part of unit is marine; the upper part is interpreted to be non-marine to estuarine. **MIbc** is mapped extensively in the park to the east of the Chalone Creek fault and the Pinnacles fault.
	Miocene	Monterey Formation, undifferentiated (**MIm**)	Thin beds of white to light gray-brown siliceous shale. **MIm** is minorly exposed in valleys at the northern park boundary.

Eventually, around 3.5 million years ago, a "final" round of regional tectonic uplift brought the central Coast Ranges and the Pinnacles Volcanic Formation above sea level, pushing the coastline farther seaward and exposing the Salinas Valley (Page et al. 1998; Howard 1979). The Neogene sedimentary rocks in the park are capped by the Quaternary and Neogene age Paso Robles Formation (**QTp**)—a mix of fluvial and alluvial gravels that washed off the Gabilan Range to the north and the Diablo Range to the east. This change in sediment source signals a switch from west–east drainage to east–west. The increased elevation triggered the development of streams and initiated the erosion that removed the thin layer of overlying sedimentary rocks and began to erode the Pinnacles Volcanic Formation into the striking landscape of today (fig. 13).

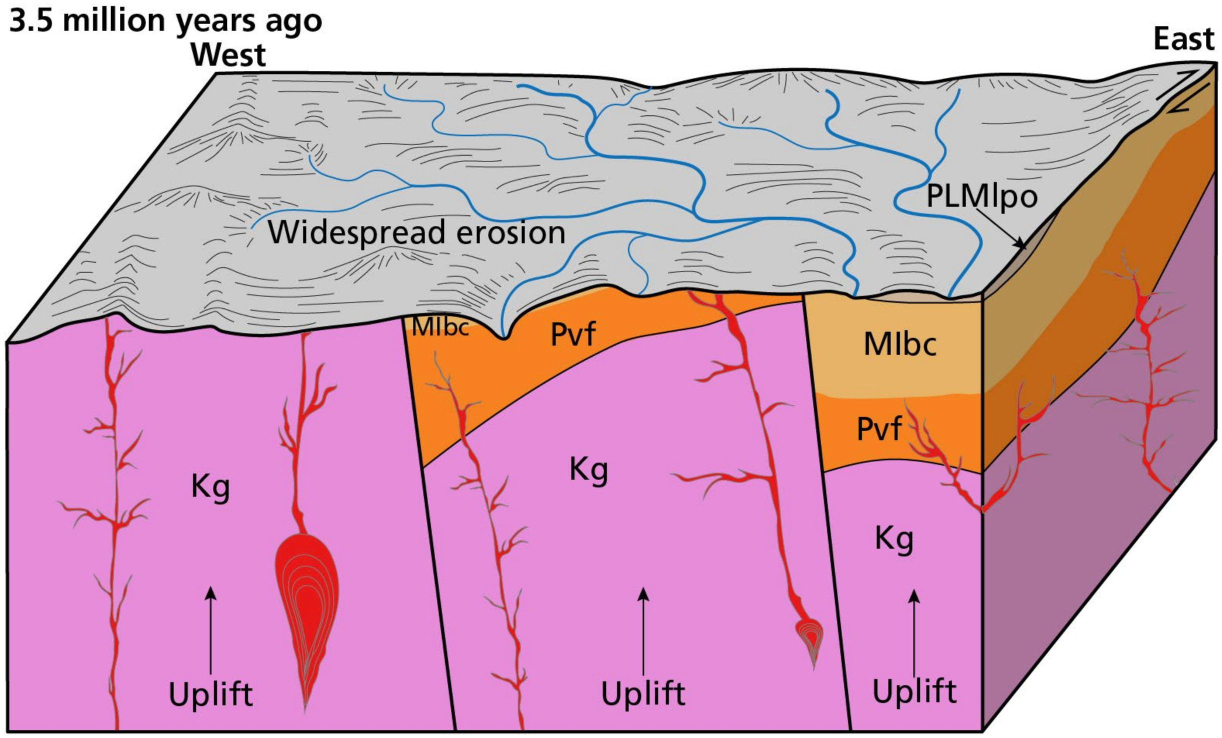

Figure 13. Diagram of uplift and erosion of Pinnacles Volcanic Formation.
3.5 million years ago a "final" round of tectonic activity lifted the entire region and triggered the development of streams which cut down through the thin covering of sediment and into the Pinnacles Volcanic Formation. This set the stage for the modern landscape of the park—Cretaceous granite in the west, the Pinnacles Volcanic Formation in the center, and sedimentary rocks in the east. Kg signifies generalized Cretaceous granite; Pvf signifies Pinnacles Volcanic Formation; MIbc signifies Bickmore Canyon Arkose; PLMIpo signifies Pancho Rico Formation; arrows indicate direction of fault movement or uplift. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Quaternary Period (2.3 million years ago to present)

The last two million years of the park's geologic story has been marked by continued tectonic uplift, erosion of the Gabilan Range and the Pinnacles Volcanic Formation, and surficial deposition. Streams and rainfall runoff, invigorated by the elevated land surface, etched the soft and fractured volcanic rocks and carved the deep, narrow valleys that define the area (Howard 1979; fig. 14). Rainwater seeped into fractures in the rock, altering and weakening the rock and creating the locus for further erosion. Weakened fractures allowed huge blocks of Pinnacles breccia (**MIOLpbr**, **MIOLpbb**, **MIOLpbt**) to detach and fall from the cliffs and steep slopes, becoming wedged in the narrow valleys to form talus caves. Landslides (**Qls**) and streams (young and old alluvium) deposited finer-grained material along the bases of hills and the valley floors, processes that are still ongoing. These "surficial deposits" refer to the unconsolidated sediments lying on the ground surface, typically above bedrock. Various geologic agents such as rivers, tributary streams, wind, and gravity work these sediments into landforms such as terraces, alluvial fans, and talus. Table 7 describes surficial deposits mapped in the park.

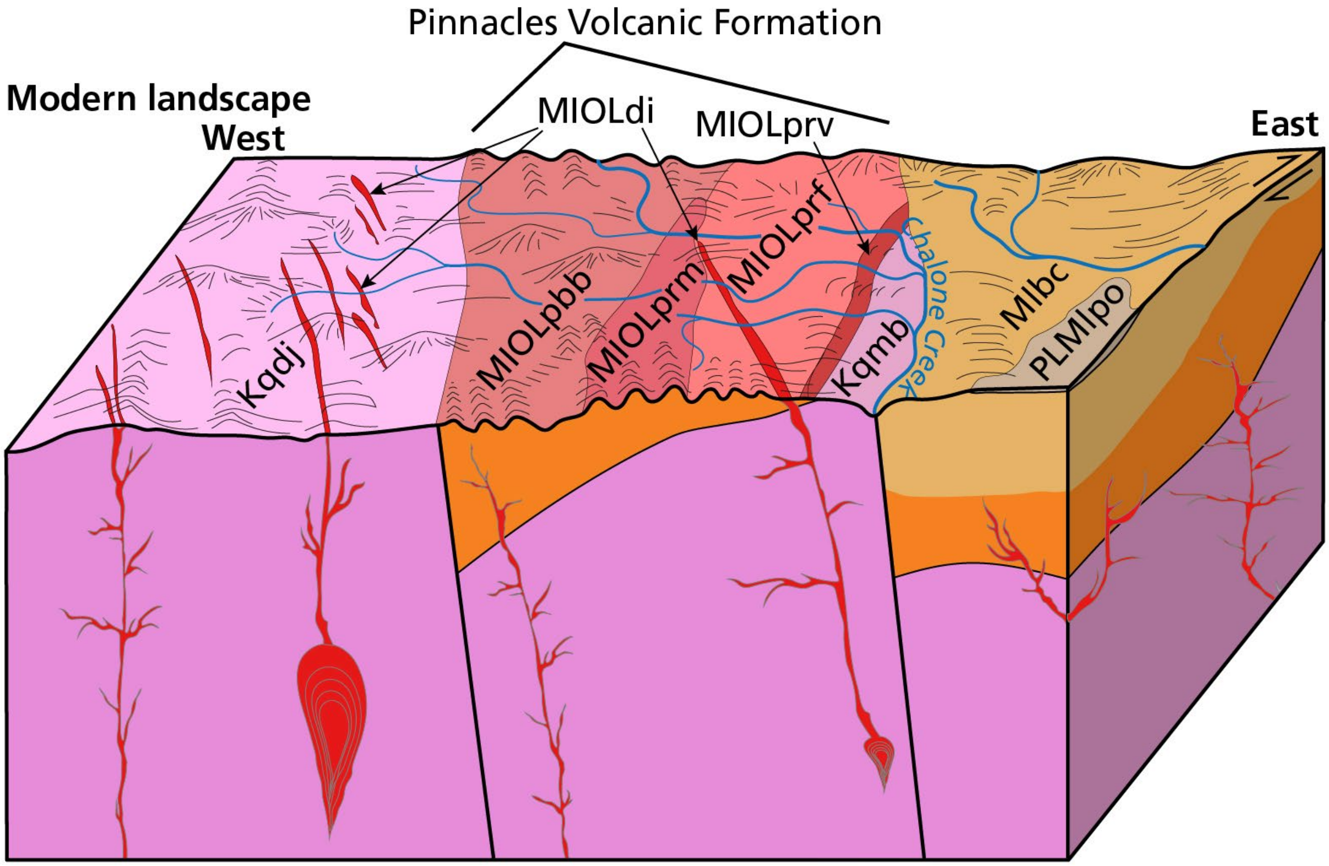

Figure 14. Diagram of the modern Pinnacles landscape.
The rocks of the Pinnacles Volcanic Formation (MIOLpbb, MIOLprm, MIOLprf, MIOLprv, MIOLdi) are exposed at the surface. Weathering and erosion along joints and fractures in the volcanic breccias (e.g. MIOLpbb) created the distinctively eroded landscape of rock pinnacles and talus caves and exposed the Cretaceous quartz monzonite of Bickmore Canyon (Kqmb) in the southeastern area of the park. In the west, the Cretaceous granitic basement (Kqdj) and the volcanic "plumbing" dikes (MIOLdi) are exposed. To the east, sedimentary rocks (MIbc, PLMIpo) cover the volcanic and basement rocks. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Matthews (1973).

Table 7. Quaternary surficial deposits mapped in Pinnacles National Park.

The most recent deposits in the park (Qsc, Qva, and Qyf) reflect active depositional processes. Period and epoch colors are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps. Geologic map unit colors correspond to the colors used on map poster. Unit descriptions are from Matthews (1973), Wagner et al. (2002), and Rosenberg and Wills (2016). Detailed descriptions of these units are available as part of the GRI GIS data in the pinn_geolgoy.pdf (see "GRI GIS Data" in the "GRI Products" section of this report).

Epoch	Geologic Map Unit (map symbol)	Description
Holocene	Modern stream channel deposits (**Qsc**)	Unconsolidated, moderately well-sorted gravel, sand, and silt in active or recently active streambeds. In the park, **Qsc** is mapped in the Chalone Creek and Sandy Creek streambeds.
Holocene	Young alluvium, undifferentiated (**Qya**)	Unconsolidated gravel, sand, and silt in active or recently active floodplains. Deposits are near the locus of recent sedimentation, although the most recently active surfaces are mapped as **Qsc** in some areas. **Qya** is mapped throughout the park along streambeds, especially Sandy Creek, Chalone Creek, and Bear Creek.
Holocene	Young alluvial fan deposits (**Qyf**)	Unconsolidated gravel, sand, and silt deposited from flooding streams and debris flows. Deposits are clearly related to ongoing depositional processes. Within the park, **Qyf** is mapped in a small area of Chalone Creek along the South Wilderness Trail.
Pleistocene? to Holocene	Landslide deposits (**Qls**)	Rock detritus from bedrock and/or surficial material, broken in varying degrees, and deposited by landslide processes. Most deposits are Holocene, but some may be as old as late Pleistocene. Generally, only landslides between 10,000 m^2 (0.004 mi^2) and 50,000 m^2 (0.02 mi^2) are shown to preserve the clarity of underlying bedrock. **Qls** is mapped throughout the park.
Pleistocene to Holocene?	Older alluvium, undifferentiated (**Qoa**)	Unconsolidated to moderately indurated gravel, sand, and silt deposited on flood plains. Deposits have been uplifted or otherwise removed from recent sedimentation and may be dissected in varying degrees; and can show moderately to well-developed soils. Within the park, **Qoa** is mapped in a few small outcrops along Bear Gulch and Bear Creek.

Geologic Features and Processes

The geologic features and processes highlighted in this chapter are significant to the park's landscape and history. Selection of these features and processes was based on input from scoping and conference-call participants, analysis of the GRI GIS data, and research of the scientific literature and NPS reports.

Pinnacles Rock Formations

The namesake pinnacles of the park are the eroded remains of volcanic flows and pyroclastic layers of primarily rhyolite in the Pinnacles Volcanic Formation (see table 5). The pinnacles stand in stark contrast to the surrounding rolling hills of Cretaceous granite, a testament to how differently the rock types erode (Alt and Hyndman 2000). This difference is slightly surprising because the igneous rocks—granite and rhyolite—are very similar chemically and mineralogically; however, grain (crystal) size is larger and more susceptible to erosion in granite (Alt and Hyndman 2000).

The volcanic material was erupted around 22 million years ago in a series of violent eruptions. Extrusive lava fused together with fragments of rock, volcanic ash and glass, and other pyroclastic materials. Subsequent tectonic activity along the San Andreas Fault separated the Pinnacles Volcanic Formation from the Neenach Volcanics. Part of the Pinnacles Volcanic Formation was dropped down into a graben (fault-bounded tectonic basin) and submerged beneath a shallow sea (see "Geologic History" chapter). While marine sedimentary rocks accumulated on top of the Pinnacles Volcanic Formation, the uplifted Neenach Volcanics were swiftly eroded. Today, the Neenach Volcanics—the eastern half of the volcanic field—is just a few red outcrops on a hill. A geocacher described the site saying, "don't expect too much, there's a reason this part didn't become a national park" (Geocaching 2005). No active volcanism is occurring at the park today, however calling Pinnacles a "volcanic park" seems appropriate based on its geologic past. See the "Geologic History" chapter of this report for detailed information about the formation and erosion of the Pinnacles Volcanic Formation.

The various volcanic rock types, including rhyolite, andesite, dacite, tuff, and agglomerate make up the most distinctive features at the park, including the namesake rock pinnacles, and are prominent in the GRI GIS data (see GRI poster).

Volcanic breccia (geologic map units **MIOLpbb**, **MIOLpbt** and **MIOLpbr**) is formed when lava from explosive eruptions rips through the volcanic neck taking rocks with it and mixing them with lava, ash, and volcanic glass. The breccia in the park is composed of sharp angular fragments of rhyolite (volcanic rock high in silica [SiO_2]) embedded in a welded matrix of lava and ash, ranging in color from reddish to grey (fig. 15). The fragmentation of the rhyolite in the park attests to the violent nature of the eruption (NPS 2005).

Tuff is consolidated or cemented volcanic ash and lapilli (pyroclastic material 2 mm to 64 mm in size). One of the tuff units at the park (**MIOLpbt**) contains marine microfossils (ostracodes), indicating that the volcanic field was partially submerged for a portion of the eruptive period (see "Paleontological Resources"). The tuff also locally includes reddish fragments of rhyolite (Matthews and Webb 1982).

Figure 15. Photograph of volcanic breccia at Pinnacles National Park.
The violent eruptions of the Pinnacles Volcanic Formation resulted in the formation of volcanic breccia. The angular clasts in the rock were caught up in the erupting lava and ash and cemented together when the finer-grained material between the clasts cooled. The surface of these rocks makes them popular for rock climbing. Photograph by Rebecca Port (National Park Service).

Cliffs and Spires

The erosion that produced the cliffs and spires of the Pinnacles Volcanic Formation only began about 2 million years ago as the rocks were uplifted, increasing the energy and erosive power of streams in the Gabilan Range (Howard 1979). The episodic nature of the volcanic eruption, combined with the various sizes and compositions of the components of the rock units, produced a rock formation crossed by many vertical joints (cracks in the rock). A long history of faulting and tilting further fractured the rock with joints that extend through many layers. The breccia units (**MIOLpbb** and **MIOLpbr**) are the primary cliff-forming rocks in the park. The surfaces of the joints were exposed to chemical and physical weathering by water and air. Furthermore, erosion by running water, including the debris carried in water which acts like sandpaper, gouged out rocks and potholes. The result has been the formation of vertical cliffs, distinctive weathered spires, and knobby peaks (fig. 16).

Figure 16. Spheroidal weathering of rock pinnacles. Weathering and erosion of the volcanic breccia that was fractured and jointed during cooling and subsequent tectonic upheaval, produces the distinctive spires and knobby peaks of the namesake rock pinnacles. Photograph by Rebecca Port (National Park Service).

Layers of volcanic breccia at Balconies Cliffs dip toward the northwest. The red layer (fig. 17) in the middle of the cliff is a weathered ash bed that was baked by the heat of a subsequent volcanic eruption. The Balconies Cliffs are important habitat for prairie and peregrine falcons, with up to three nests located on the cliffs each year (Paul Johnson, Pinnacles National Park, wildlife biologist, written communication, 30 March 2022; see "Native Species and Ecological Processes" in "Geoheritage Values of Park Resources" section).

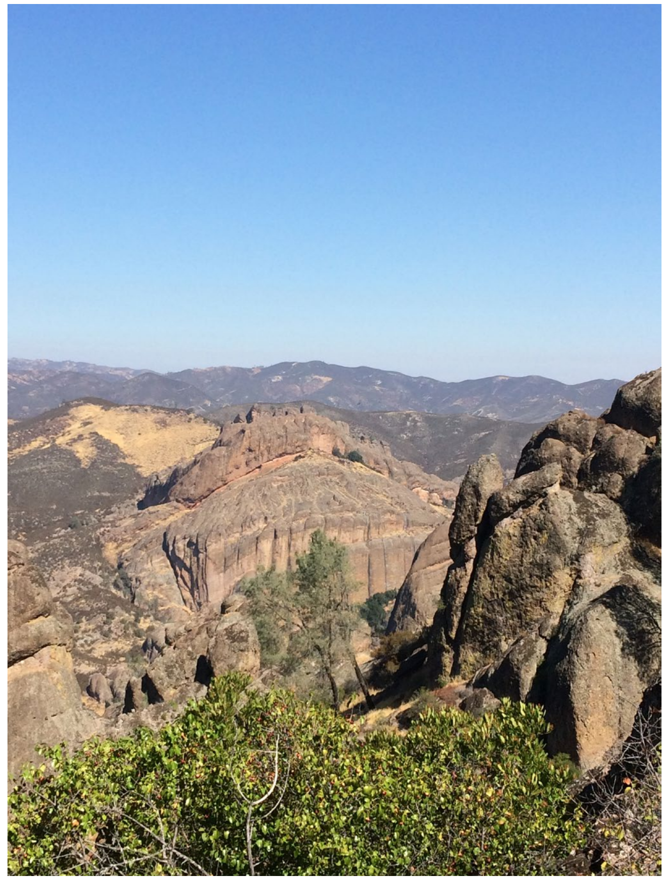

Figure 17. Photograph of Balconies Cliffs. Balconies Cliffs, as seen from the High Peaks area. The breccia units of the Pinnacles Volcanic Formation (e.g., MIOLpbb) form cliffs as wind and water erode the joints in the rock. The tilted layers of volcanic breccia intersect with near vertical joints, creating spires that weather to the rounded forms visible in the foreground. The red layer visible in the Balconies Cliffs is an ash layer that was baked by subsequent eruptions. Photograph by Rebecca Port (National Park Service).

The High Peaks consists of layers of relatively strong, well-consolidated breccia (**MIOLpbb**) interlayered with volcanic ash and rhyolitic lava flows (**MIOLpbr**). Burial and compaction hardened these layers into the consolidated rock we see today. Recent faulting, fracturing, and erosion have sculpted these rock layers into vertical cliffs and spires that reach several hundred feet high. Hawkins Peak, the tallest point in the High Peaks, is more than 830 m (2,700 ft).

Active processes contribute to landscape evolution. Minerals precipitate from water draining over the cliffs, leaving dark stains on the rocks. In some places, weathering of the volcanic rocks has created a surface which resembles a pahoehoe-style lava flow (fig. 18), although at a much larger scale. However, because so much material has been eroded it is unlikely that any flow or cone features remain. The volcanic rock which resembles a flow is actually breccia which erupted explosively and has been eroded along curved joints (Matthews and Webb 1982).

Figure 18. Photograph of eroded Pinnacles Volcanic Formation.
Erosion of this brecciated lava created a pattern similar to that seen in Hawaiian pahoehoe lava flows, although at a much larger scale. However, given the amount of material that has eroded it is unlikely that any complete lava flows are preserved. Minerals precipitated from flowing water stained the rocks to a dark color. Photograph by Rebecca Port (National Park Service).

Ancient Slope Movements

Slope movements have always been a part of the park landscape. During scoping (KellerLynn 2008), Vince Matthews (Colorado Geological Survey, retired) mentioned lahars deposited agglomerate (**MIOLpag**) during Miocene volcanism (23 million years ago). Although much of the breccias (e.g., **MIOLpbb**, **MIOLpbr**) were formed from pyroclastic flows, some of the layers of breccias are thought to have formed as the result of material slumping off the sides of the volcanoes near the vents, causing large landslides. The volcanoes were near water and some of the landslides likely traveled as massive turbidity currents under water that spread the material considerable distances until coming to rest near distant edges of the volcanoes. The breccia-tuff unit (**MIOLpbt**) contains disarticulated marine microfossils (ostracodes), which supports this theory. Today, significant amounts of talus, which produces the caves in the park, are evidence of past slope movements.

Talus Caves

Caves are naturally occurring underground voids that are enterable by humans. Caves are formed in a variety of ways and in a variety of rock types. Cave types include solutional caves (commonly associated with karst), volcanic (e.g., lava tubes), littoral (sea caves), talus caves (voids among collapsed boulders), regolith caves (formed by soil piping), and glacier caves (ice-walled caves) (Toomey 2009). 191 NPS units contain or potentially contain caves, karst, and/or pseudokarst (Land et al. 2013). The NPS Cave and Karst website, https://www.nps.gov/subjects/caves/index.htm, provides more information.

Despite the volcanic history of the area, no lava tubes are known to exist. Instead, weathering (e.g., freeze/thaw and earthquakes) and erosion shaped the pinnacles and created conditions for rockfall which formed the talus caves. Talus caves are rare in the NPS, with only three parks documenting their occurrence (Yosemite National Park and Glen Canyon National Recreation Area, in addition to Pinnacles National Park).

Talus caves form when rockfall creates an enclosed space, such as over the narrow canyons in the park. The talus caves at the park are composed of igneous rock. Feldspar minerals in the joints of the volcanic rock weathers easily to clay, loosening the larger blocks to be eroded away, and creating narrow slot canyons up to 40 m (130 ft) deep. Continued erosion of the canyon walls produces rockfall, which becomes lodged in the narrow canyons. Flowing water through the canyons carves both the bedrock and the fallen boulders, and, as a finishing touch, precipitates mineral deposits throughout the caves. The majority of rockfall that filled the fractures at the park is thought to have occurred during the last series of ice ages when rainfall, and thus stream erosion, was greater than today. The process of weathering and rockfall, however, continues to some extent to this day.

Other types of caves may exist in the park, but none have been documented. Conditions in the park may allow for the formation of regolith caves. The park contains no karst or pseudo-karst (Land et al. 2013); therefore, solutional caves are not likely. The conditions for sea, lava tube, or glacier caves do not exist at the park.

There are two main areas of caves in the park: the Balconies Caves near the Chaparral day-use area, and Bear Gulch Caves near headquarters (see fig. 2). The caves are popular destinations for visitors and wildlife. In the 1930s, the Civilian Conservation Corps (CCC) built trails through the caves (fig. 19), constructing stairways and bridges in order to navigate the caves without the use of ropes and ladders (KellerLynn 2008). In addition to the caves, the canyon walls above Bear Gulch Caves have formed alcoves and grottos where large boulders have weathered out of the volcanic matrix. Although most of these are small, some are large enough to fit “platoon-sized groups” (Rogers 2005). Rogers (2005) produced detailed maps and descriptions of both Bear Gulch and Balconies Caves.

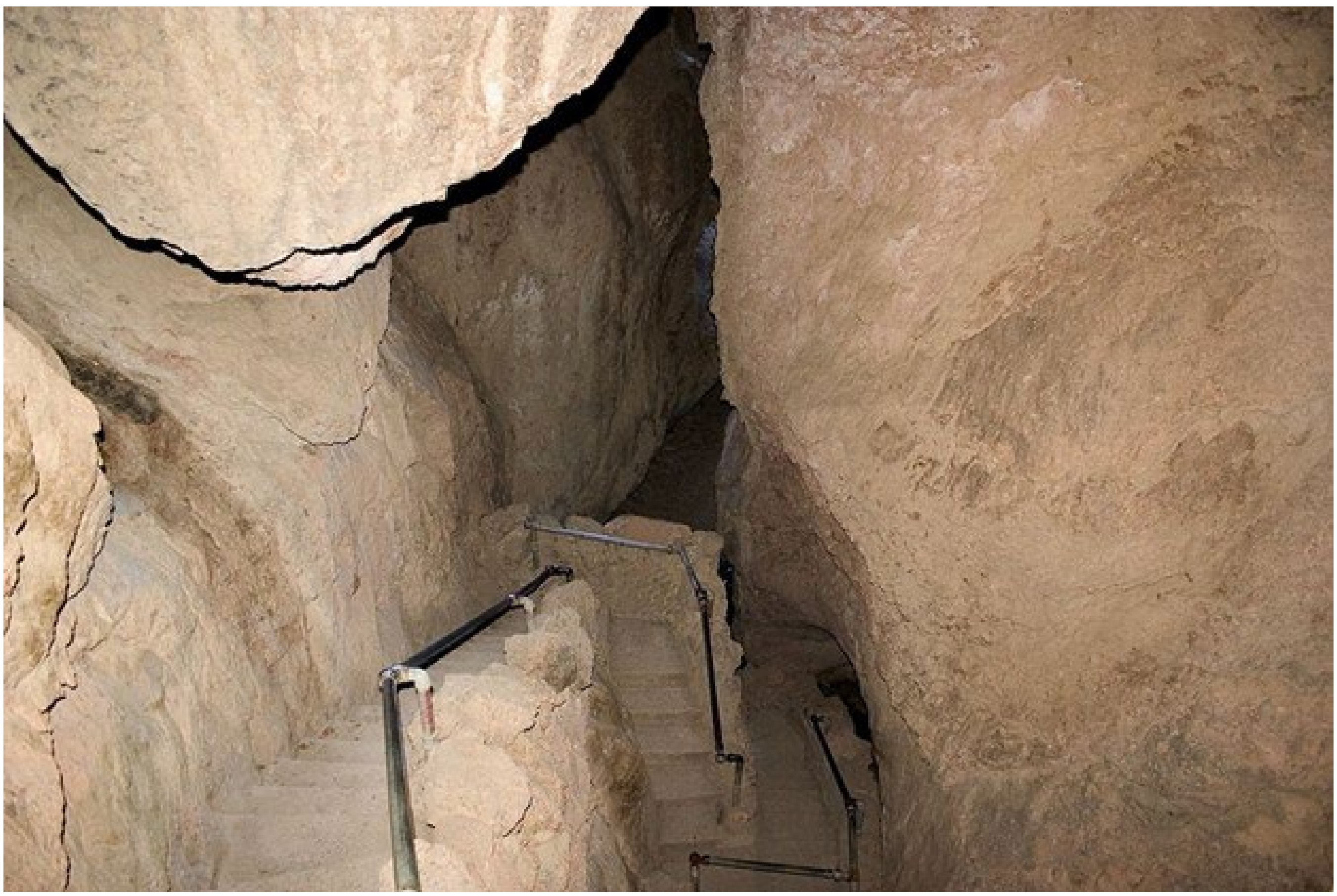

Figure 19. Photograph inside Bear Gulch Caves.
The photograph shows a pathway through a short talus cave. The pathway was constructed by the CCC in the 1930s. National Park Service photograph.

Bear Gulch Caves

Bear Gulch Caves consists of around 1,754 m (5,755 ft) of total passageways, floored alternately by unconsolidated granitic sand and gravel, and volcanic bedrock (Rogers 2005). Mineral precipitate decoration in the cave includes gypsum ($CaSO_4 \cdot 2H_2O$), birnessite ($MnO_2 \cdot nH_2O$), cristobalite (SiO_2), and seasonal ice (H_2O). These deposits form when minerals from the volcanic rock are dissolved by flowing water and precipitated in the caves. Standout features of Bear Gulch Caves include the "Rotunda," or "Bandit Room," which is capped by a single 30 m^2 (330 ft^2) boulder and contains a seasonal and variable water feature, "Mirror Lake;" and the "Inner Sanctum," a 300 m (985 ft) complex of intersecting passages (Rogers 2005). The "Reservoir Entrance" opens into an area that was once part of the cave system but has since collapsed back into an open canyon. The portion of Bear Gulch that is submerged by the reservoir is in a wider section of the canyon and therefore unlikely to form talus caves.

Balconies Caves

The Balconies Caves are smaller, consisting of about 176 m (577 ft) of passageway along the north fork of Chalone Creek Canyon, between the Balconies and the Machete cliffs. Parts of the Balconies Caves have been polished "mirror bright" by sediment-bearing floodwaters (Rogers 2005). The cave includes several large amphitheaters and at least one 15 m (50 ft) waterfall that is navigated by CCC passages. The CCC also "improved" a small spring in the cave by adding a pipe and small basin (Rogers 2005).

Bats

The park is habitat for at least fourteen species of bat, with seven having special status (NPS 2006a, 2011; see "Native Species and Ecological Processes" in "Geoheritage Values of Park Resources" section). Most bats roost in the caves but a few species roost in trees and their fur resembles tree bark (NPS 2011). A colony of western mastiff bats inhabits the Balconies Cave (Soto 2013).

Several hundred Townsend's big-eared bats roost and hibernate in different parts of Bear Gulch Cave. The colony was first documented in the park in 1997 (Rogers et al. 2003). This is the largest known colony between San Francisco and the Mexican border. Throughout most of the year, bats only use the upper portion of the cave but during maternity season they use the entire cave. They also leave the cave entirely for short periods during the spring and fall. This information was used to develop a cave management plan for Bear Gulch Cave to protect the bats (NPS 2011). See the "Geologic Resource Management Issues" section for more information about bats and cave management.

Opal Speleothems

The non-carbonate talus caves at the park are not decorated with the calcite stalagmites, stalactites, and other speleothems (geological formations created by mineral deposits that accumulate over time) common to solution caves. However, opal speleothems do occur and have the potential for scientific study.

Opal is hydrated silica ($Si0_2 \cdot nH_20$) that forms from a solution of silicon dioxide and water. As water runs through the subsurface, it picks up silica from silicate-rich rocks like the volcanic rocks in the park. When the silicate water enters a cavity, such as a fossil or cave, water evaporation results in a silica deposit. This process repeated over long periods of time eventually forms opal. To form, Opal requires a falling of the water table which concentrates silica in solution; this condition can be driven by alternating precipitation patterns.

Scientists are studying the potential to learn about past rainfall and moisture records from opal speleothems that are approximately 16 thousand to 3 thousand years old (Oster et al. 2015, 2017). A combined analysis of uranium isotopes (often present in opal) and oxygen isotopes in the opal may reveal a record of Holocene precipitation variability. The uranium isotopes can be used to determine the age of the opal, and the oxygen isotopes can be used to infer changes in precipitation or aridity over the time the opal formed (Oster et al. 2017). Further study is needed to determine if other factors may influence isotope concentration in opal. If these methods prove successful they could be employed on the opal speleothems in the park.

Faults and Folds

A fault is a fracture in rock along which movement has occurred. The three primary types of faults are normal faults, reverse faults, and strike-slip faults (fig. 20). Active faults can manifest themselves in the landscape as offset features, including street curbs, road lines, fences, and streams. Erosion tends to be enhanced along faults because of the shearing and grinding of the adjacent rocks; faults are commonly associated with linear valleys, side-hill benches, saddles in ridgelines, and other topographic features (Russ Graymer, US Geological Survey, geologist, written communication, 1 April 2022).

Three named faults cross the park: Chalone Creek, Pinnacles, and Miner's Gulch faults (Davis et al. 2013). The regional geologic map (PINN dataset; see GRI poster) shows only three faults in the park. The detailed geologic map (PIVF dataset) does not include the unnamed fault visible on the regional map across Bear Gulch Reservoir, but it does include many others not on the regional map.

In many cases, the faults line up with geologic contacts, separating the Pinnacles Volcanic Formation from the Cretaceous basement rocks (**Kgdj**, **Kgdg**) to the west and the Bickmore Canyon arkose (**MIbc**) to the east. All faults are described as "unknown offset/displacement" in the GRI GIS data.

As indicated by the US Geological Survey Quaternary fault database, none of the faults that exist within the park boundary have been active in the past 1.6 million

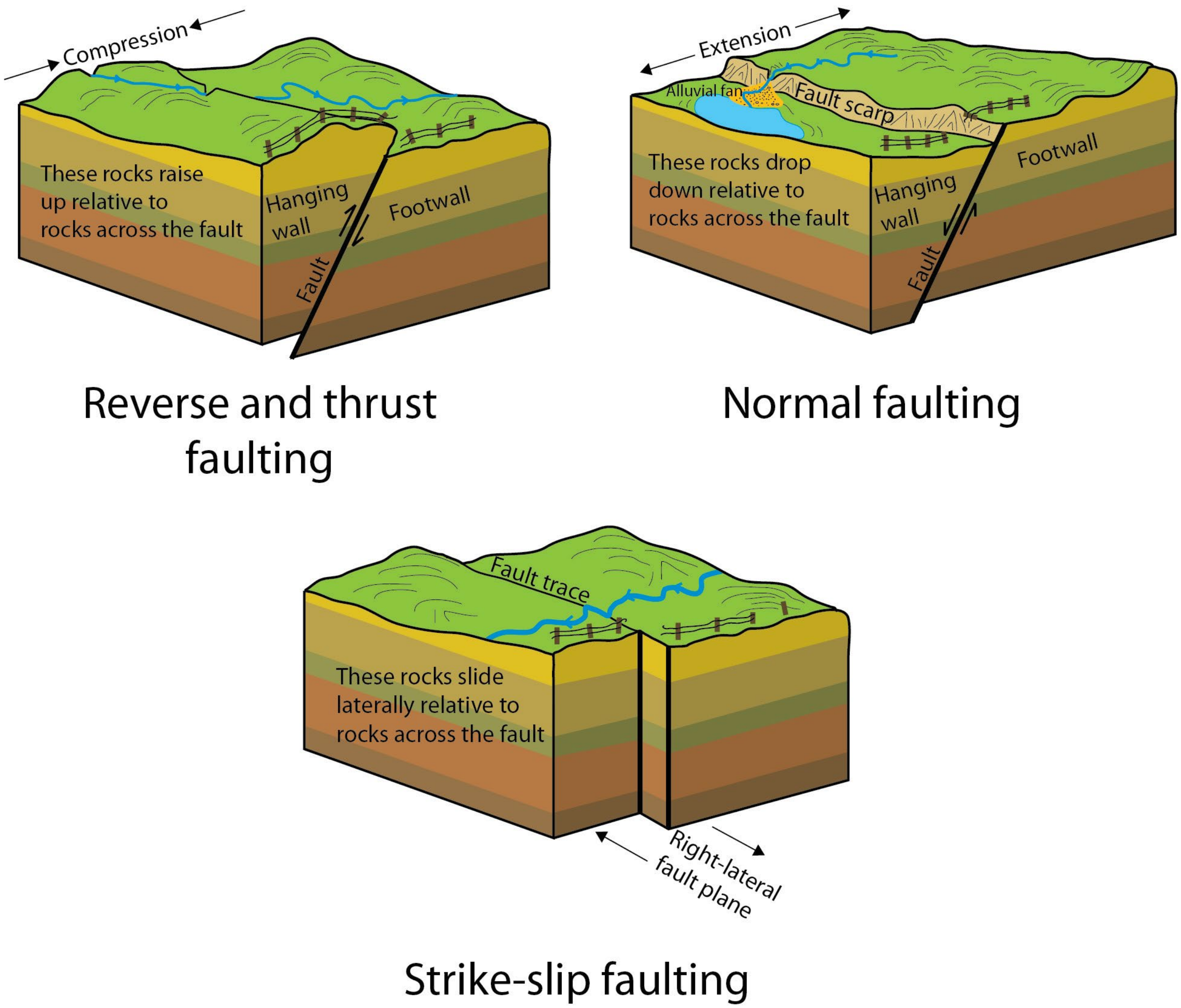

Figure 20. Graphic of the different types of faults.
Faults, or breaks in rock along which there is movement, are classified based on the direction of relative movement across the fault. In reverse or thrust faults the hanging wall moves up relative to the footwall. In normal faults, the hanging wall drops down. In transform or strike-slip faulting, one block moves laterally relative to the other. The graben that dropped down and preserved the Pinnacles Volcanic Formation was bordered on both sides by normal faults (see figure 10). The Chalone Creek fault, and the San Andreas Fault zone, are examples of strike-slip faults. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

years. However, the San Andreas Fault zone, which exists just northeast of the park, contains many active faults (US Geological Survey and California Geological Survey 2022). The town of Hollister—about 50 km (30 mi) north of the park—is famous among geologists as a town built on a section of the Calaveras Fault (a strand of the San Andreas Fault system) that exhibits "fault creep," or continuous but very slow movement (fig. 21). Residents began to notice movement of the sidewalk in 1929. It creeps only about 0.25 inches (0.3 cm) a year, not nearly as fast as the San Andreas Fault (Russ Graymer, written communication, 1 April 2022).

Figure 21. Offset sidewalk in town of Hollister, California.
Gradual but persistent strike-slip movement known as "fault creep" along the Calaveras Fault has visibly offset this sidewalk. By measuring how far the sidewalk has moved since it was "fresh," geologists can determine the rate of movement along the fault. Photograph by Garry Hayes (GeoTripper), used by permission.

Graben

A graben is a down-dropped fault block adjacent to a normal fault (see fig. 20). The relatively uplifted block is called a horst. Horst and graben landscapes typically develop as a result of crustal extension; the Basin-and-Range area of the United States between the Rocky Mountains and Sierra Nevada is a series of horsts and grabens (Graham 2014). The area between the Pinnacles and Chalone Creek faults with the exposed Pinnacles Volcanic Formation rocks is a half-graben (down-dropped relative to the west side, but not the east; Hinds 1968). In the late Miocene (about 12 million years ago), parallel cracks developed across the volcanic field and a large section of the volcanics dropped down along these faults. Had this graben not formed and protected the volcanic rocks, Pinnacles National Park would likely not exist today as the rocks which later formed the distinctive pinnacles would have long since eroded away (Howard 1979). The evidence for this is in what remains of the Neenach volcanics (see "Geologic History").

About 6 million years ago, the Pinnacles and Chalone Creek faults were mostly abandoned, and slip became concentrated onto the San Andreas Fault zone to the east. The Chalone Creek fault is a clear indication of the former extent and complexity of the San Andreas Fault zone (Matthews and Webb 1982).

San Andreas Fault

The San Andreas Fault trace is the major fault that defines the San Andreas Fault zone, a group of faults roughly parallel to the San Andreas Fault. The fault zone is in turn a part of the San Andreas Fault system, a suite of interconnected faults that run along the Pacific rim of North America. The fault, zone, and system are all components of the active boundary between the North American and Pacific tectonic plates.

The "Geologic History" chapter of this report describes the formation and evolution of the San Andreas Fault system as it relates to the story of the park, and the potential for earthquake related hazards is discussed in the "Geologic Resource Management Issues" chapter. Movement along the fault system is central to the geologic story of the Pinnacles Volcanic Formation, but the park is only a tiny part of the San Andreas Fault.

The park is adjacent to the "creeping" section of the San Andreas Fault, where friction is low enough that the fault slips more or less continuously, and stress does not significantly build up. For this reason, no major earthquakes have been caused by the fault here in historic time, though seismographs do record many small earthquakes, most too weak to feel (Alt and Hyndmann 2000). Other earthquakes generated from farther away, most measuring magnitude-2 (on the Richter scale) are commonly felt by visitors and staff in the park or heard as distant sonic booms.

Folds

Folds occur when rocks are subjected to stress and bend rather than breaking. Erosion of folded rock units can create symmetrical patterns around the axis of the fold. In a syncline (U-shaped fold), younger rocks are in the center with older rocks to the outside; the opposite is true in an anticline (A-shaped fold).

In the northern part of the park, two mapped anticlines plunge toward each other in the Bickmore Canyon arkose (**Mlbc**); one plunges northeast and the other southwest (see GRI poster).

The Paicines and Vallecitos synclines are mapped northeast of the park along with several small unnamed folds nearby. These folds are roughly parallel to the faults northeast of the park and probably formed by the same tectonic forces that also tilted the structural block between the Pinnacles and Chalone Creek faults. Faults and folds are included in the GRI GIS data.

Fluvial Features and Processes

Fluvial features and processes are those related to flowing water, including the erosion and deposition of sediments. Erosion by streams has been a major contributor to carving the distinctive park landscape. Streams transport material from hills to lower elevations; some of this material is deposited in active floodplains, the remainder is carried to the ocean where it is deposited offshore (Rosenberg and Wills 2016). Modern fluvial deposits in the park include map units **Qsc**, **Qya,** and **Qyf** (see table 7). The rugged terrain of the Gabilan Range does not produce regular dendritic drainage patterns; rather, streams follow faults and fractures in the rock which often intersect at right angles (Davis et al. 2013).

Pinnacles National Park lies almost entirely within the Chalone Creek watershed which drains into the Salinas River before emptying into Monterey Bay. Scoping participants estimated that 32 km (20 mi) of streams run through the park (KellerLynn 2008). Many of these streams are intermittent (drying up during summer or fall) or ephemeral (flowing during and shortly after storms). Creek beds at the park are commonly lined with porous alluvium. During a storm, a creek may become a roaring cascade, but water quickly percolates beneath the surface after the rain ceases (Ewing 1996).

Stream-side wetlands are the most common form of wetlands found in the park and are monitored by the NPS San Francisco Bay Area Inventory & Monitoring Network (SFAN) in order to detect habitat change (fig. 22). See the SFAN website for Pinnacles National Park, https://www.nps.gov/im/sfan/pinn.htm, for a complete list of vital signs monitored at the park and associated reports. Wetlands at the park host a diversity of native vegetation and animals, including the federally threatened California red-legged frog. Possible loss or reduction of these wetlands (see “Climate Change”) poses a risk to habitats and wildlife in the park.

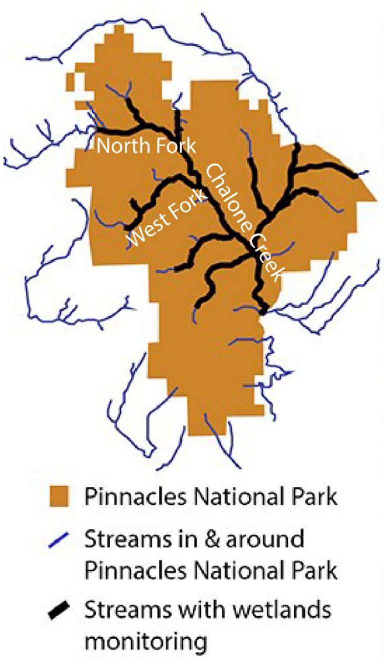

Figure 22. Streams and Wetlands in Pinnacles National Park.
The majority of streams in the park are monitored for vital signs that could provide early warning of ecosystem changes. Diagram on the left shows the streams in and around the park, and those that currently have wetlands monitoring. Photograph on the right is of the habitat along the West Fork Chalone Creek. Diagram and photograph by Jessica Weinberg McClosky (National Park Service).

Chalone Creek

Chalone Creek originates approximately 6.4 km (4 mi) northwest of the park boundary and flows the length of the park to the southeast corner (see GRI poster). Chalone Creek drains both the west and east sides of the park. Chalone Creek contributed significantly to the formation of the talus caves; the creek undercuts beds of massive breccia to the extent that, in places, the overlying breccia has slumped or fallen down to form the caves (Hinds 1952). Chalone Creek and its tributaries have a history of flooding and debris flow (Meyer 1995), this is discussed in detail in the "Flooding" section of the "Geologic Resource Management Issues" chapter of this report.

Ancient Fluvial Processes

Fluctuating sea levels and local tectonics during the Pleistocene (2.6 million to 12 thousand years ago) resulted in a complex series of estuarine and alluvial deposits (during high sea levels), and erosion of these deposits into a series of stream terraces (during low sea levels) (KellerLynn 2008). Stream terraces are the "steps" that extend along the side of a river valley and represent a former floodplain elevation of the stream. The stream terraces in the Gabilan Range record periods of uplift and the associated erosion of stream canyons through the ranges. The terraces and alluvial fans characterize the landscape of the Salinas Valley and form the aquifer that supplies much of the area's water (Tinsley 1975; see "Groundwater and Springs").

Agglomerate—a mix of rounded boulders and smaller material—is evidence of ancient fluvial activity. Boulders of volcanic rock were rounded by an ancient stream which deposited them on the edge of an ancient sea. The boulders and other material then slid down the submerged sea shelf in a submarine landslide and came to rest with other fragments of all sizes. Andesite alternating with agglomerate and other rocks observable along the Condor Gulch Trail is possibly a product of deposition by a series of mudslides (Matthews and Webb 1982). The sedimentary rocks (**MIbc**, **QTp**) east of the Chalone Creek fault are fanglomerates (conglomerate deposited in an alluvial fan setting) composed of granitic and volcanic detritus shed from the Santa Lucia granitic basement (**Kgdj**, **Kgdg**) and the Pinnacles Volcanic Formation (**MIOLp** units).

Groundwater and Springs

Permanent surface water is scarce at the park. Artificial sources include Bear Gulch Reservoir and several stock ponds that dry up in drier years. Most of the water resources in the park are groundwater, originating as rainwater, seeping through permeable sand and gravel stream beds, and infiltrating at the land surface. Where alluvial deposits exist, such as in Bear Gulch and parts of Chalone Creek watershed, the infiltrated rainwater contributes to a shallow alluvial groundwater flow system, with the water table generally 0–10 m (0–33 ft) below land surface (Scheiderich et al., in press). Fractures and faults in volcanic, granitic, and sedimentary basement rock also host groundwater but to a lesser extent; many fractures have been filled with calcite, rendering them impermeable (Akers 1967).

In bedrock, where permeable fractures encounter impermeable rock, water can be forced back to the surface, forming perennial seeps and springs that usually occur on hillsides where the water table intersects land surface. During the dry season, groundwater is also the source of streamflow in perennial stream reaches, with groundwater discharging directly into the streams or adjacent channels or flowing into the streams from seeps and springs. In addition to sustaining the streams, these seeps and springs are a source of water for wildlife during the dry season and provide habitat for plants, amphibians, and aquatic life (Borchers and Lyttge 2007). Locations of named springs are shown in figure 23. Table 8 identifies these springs and describes their character.

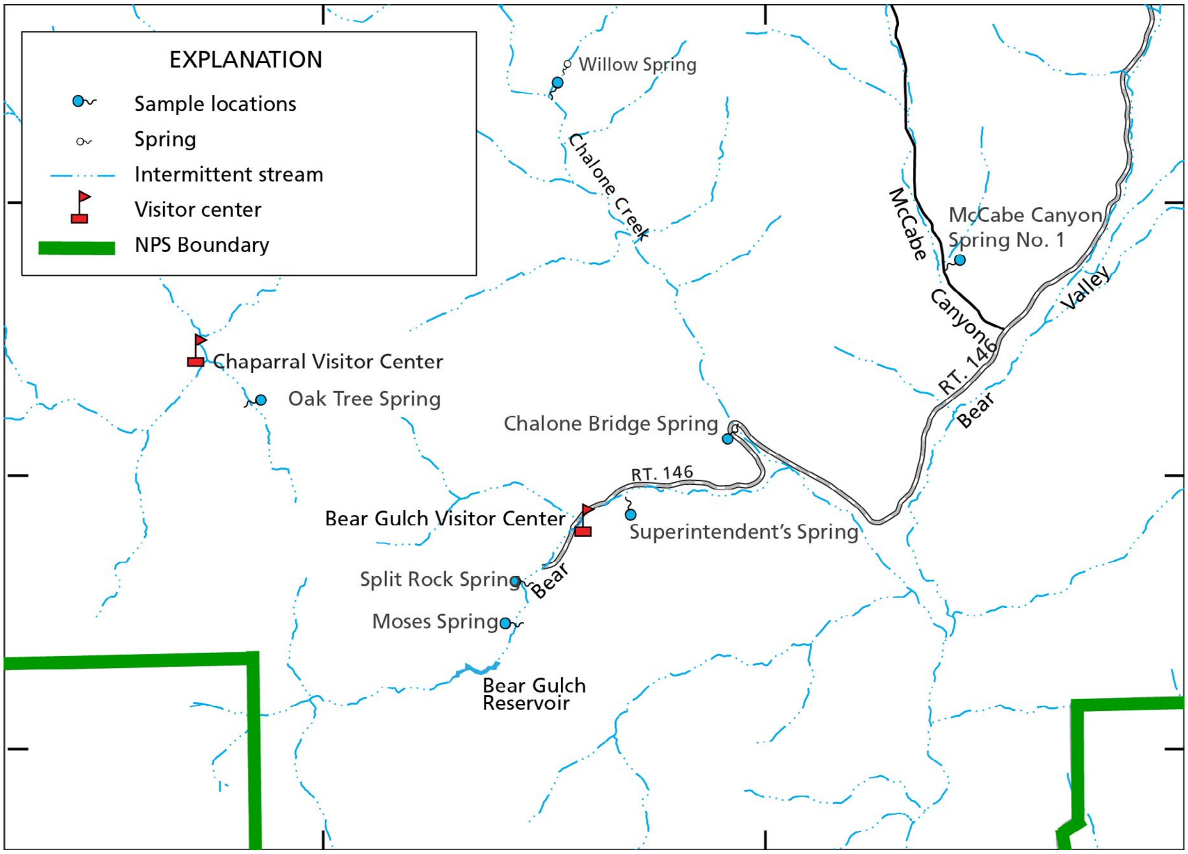

Figure 23. Spring locations in Pinnacles National Park.
Map showing the locations of named springs in Pinnacles National Park. Springs sustain the streams in the park and are the primary source of water for wildlife during the dry season, providing habitat for plants, amphibians, and aquatic life. Figure from Borchers and Lyttge (2007, figure 2) modified by Michael Barthelmes (Colorado State University).

Table 8. Springs in Pinnacles National Monument

Spring name	Notes
Willow Spring	Perennially flowing spring in a small canyon tributary to North Fork Chalone Creek. Constant discharge of about 40 gpm (151 lpm) indicates a large and stable recharge source. One of several springs that discharge at about 1,200 ft (365 m) where geologic map unit **Tsg** intersects with rhyolite, suggesting that these springs recharge from the same source.
Split Rock Spring	Located upstream from the picnic area near park headquarters, Split Rock Spring emanates from fractures in volcanic breccias and tuffs with a yield of less than 2 gpm (8 lpm). Prior to construction of wells along Chalone Creek, Split Rock Spring was the primary source of water for the park. It is protected by cement curbing but is still subject to pollution after rain and should be treated as if polluted if it is used for drinking (Akers 1967).
Oak Tree Spring	Developed in a soil or thin veneer of alluvium that temporarily stores water emanating from fractures in volcanic breccias and tuff. Yield is less than 1 gpm (4 lpm), although the spring flows perennially (Borchers and Lyttge 2007). A concrete cistern is located in dense brush east of the trail near Juniper Canyon.
McCabe Canyon Spring No. 1	Issues from granitic fanglomerate from which it has piped fine-grained material and eroded about 6 m (20 ft) into the hillslope. A marshy area has formed downslope from the spring (Borchers and Lyttge 2007). Several other spring-fed marshy areas are found elsewhere in the canyon, as well as in the Pinnacles campground.
Superintendents Spring	Issues from an opening eroded in sandy colluvium (Borchers and Lyttge 2007).
Moses Spring	Located in Bear Gulch, outflow runs down the trail slope to the northeast (Borchers and Lyttge 2007).

Lakes

The only sizeable lake in the park is Bear Gulch Reservoir (fig. 24). Located at the upstream end of Bear Gulch Cave, the dam was constructed by the CCC in 1935 and raised 4.2 m (14 ft) in 1936. Originally constructed as a source for water supply, primarily for fire suppression, Bear Gulch Reservoir now also provides habitat to the threatened California red-legged frog. The species was introduced to the reservoir as part of a reestablishment project. Sediment is filling the reservoir and park managers are considering options for preserving this habitat (KellerLynn 2008). Other water bodies in the park include some stock ponds and a small ephemeral basin.

Figure 24. Photograph of Bear Gulch Reservoir. Bear Gulch Reservoir is the only sizable lake in the park. It provides habitat for the California Red-legged frog which was introduced to the reservoir as part of a reestablishment project. Photograph by Rebecca Port (National Park Service).

Paleontological Resources

Paleontological resources (fossils) are any evidence of life preserved in a geologic context (Santucci et al. 2009). All fossils are nonrenewable. Body fossils are remains of the actual organism such as bones, teeth, shells, or leaves. Trace fossils are evidence of biological activity such as burrows, tracks, or coprolites (fossil dung). Fossils in NPS areas occur in rocks or unconsolidated deposits, museum collections, and cultural contexts such as building stones or archeological resources. As of May 2022, 283 NPS areas had documented paleontological resources in at least one of these contexts (Vince Santucci, NPS Geologic Resources Division, paleontologist, email communication to Rebecca Port, NPS Geologic Resources Division, geologist, 16 May 2022). The NPS Fossils and Paleontology website, http://go.nps.gov/paleo, provides more information.

Fossils are rare in igneous rocks because the tremendous heat associated with volcanic and plutonic activity typically destroys any organic matter. Exceptions include ash fall deposits, such as those at Florissant Fossil Beds National Monument in Colorado (see KellerLynn 2006) and Craters of the Moon National Monument in Idaho (see KellerLynn 2018). Because a portion of the Pinnacles Volcanic Formation was deposited in a marine environment, the presence of some poorly preserved marine microfossils (Matthews and Webb 1982) adds Pinnacles National Park to this list.

Will Elder (Golden Gate National Recreation Area) conducted a preliminary inventory of paleontological resources for the San Francisco Bay Area Network parks (Elder et al. 2008). Park fossils documented during the inventory included ostracodes (3 mm [0.12 in]; bivalve crustaceans) and foraminifera in volcanic tuff (**MIOLpbt**) with sedimentary structures indicating underwater deposition; and some clasts in the dacite breccia (**MIOLpd**) that resemble fossil wood and may be woody material (Phil Stoffer, US Geological Survey, personal communication to Will Elder, Golden Gate National Recreation Area, September 2007).

Graymer et al. (2018 draft) documented poorly preserved, fragmented, and/or long-ranging species of macrofossils in the Etchegoin-Jacalitos Formation (**PLMIej**), Santa Margarita Formation (**MIsm**), and the Bickmore Canyon Arkose (**MIbc**). Microfossils, which provided good age control, were documented in the Bickmore Canyon Arkose (**MIbc**), Monterey Formation (**MIm**), and the Pancho Rico Formation (**PLMIpo**). Of these units, only the Bickmore Canyon Arkose is mapped in the park (see GRI poster).

The Miocene and Pliocene (23 million to 1.8 million years ago) sedimentary rocks that surround the park are fossiliferous and stream beds in the area are known to yield fossils. The likelihood is low, but it is possible that Chalone Creek could cut through these fossiliferous layers and transport fossil-bearing material to the park to be deposited as alluvium (Phil Stoffer, US Geological Survey, personal communication to Will Elder, Golden Gate National Recreation Area, September 2007). Diatom and bivalve fragments, an echinoid, and fish scales have been found in the Monterey Formation shales immediately adjacent to the park's eastern boundary in Bear Valley (Kerr and Shenk 1925). It is possible that field investigations could uncover these fossils within the park boundary as well (KellerLynn 2008).

Paleontological resources associated with NPS caves include bat fossils and packrat middens but none are yet documented in the talus caves of Pinnacles National Park. However, their discovery is possible (Elder et al. 2008). Bats exist in the caves, so depending on how long they have inhabited these areas, bat fossils could be present (Rogers et al. 2003). Rogers et al. (2003) also notes the occurrence of packrat droppings in the caves, although no packrat middens have been documented within the park (Elder et al. 2008).

Periglacial Features

Needle ice, or "pipkrake," is a "small, thin spike or needlelike crystal of ground ice, from 2.5–6 cm (1–2.4 in) in length, formed just below, and growing perpendicular to, the surface of the soil in a region where daily temperature fluctuate across the freezing point. It is common in periglacial areas, where it contributes to the sorting of material in patterned ground and to downslope movement of surface material (Neuendorf et al. 2005). Pinnacles National Park has excellent examples of needle ice; scoping participants estimated that the crystals can reach 5 cm (2 in) or more in length.

Vince Matthews participated in the scoping trip and, in 1999, prepared a paper (Matthews 1999) about needle ice on the Tennessee-Kentucky border. He concluded that needle ice formation depends on three factors: (1) initially warm ground temperature allowing high water penetration into the soil during heavy precipitation; (2) dry stalks that serve as conduits to draw moisture out of the ground; and (3) an extremely low air temperature occurring over warmer, moist ground (Matthews 1999). Confirming studies have not been conducted at the park, but it is likely that these factors contribute to the formation of needle ice at Pinnacles National Park (KellerLynn 2008).

Geologic Resource Management Issues

Some geologic features, processes, or human activities may require management for human safety, protection of infrastructure, and preservation of natural and cultural resources. The NPS Geologic Resources Division provides technical and policy assistance for these issues (see "Guidance for Geologic Resource Management"). The issues are ordered with respect to management priority.

During the 2007 scoping meeting (see KellerLynn 2008) and the 2018 conference call, participants (see "Acknowledgements") identified the following resource management issues and potential opportunities for future study:

- Seismicity and earthquakes
- Cave management
- Flooding
- Climate change
- Slope movements
- Rock climbing
- Disturbed lands restoration
- Groundwater quality and springs
- Paleontological resource inventory, monitoring, and protection
- Oil, gas, and mineral development
- Abandoned mineral lands

The park's foundation document (NPS 2015) and natural resource condition assessment (Davis et al. 2013) are primary sources of information for resource management in the park. In 2018, a resource stewardship strategy (RSS) workshop was completed at the park and a report summarizing the workshop is available (NPS 2019).

The RSS identified "priority resources," or those "cultural and natural resources or values that the National Park Service manages or monitors to maintain a park unit's purpose and significance, to address policy/law mandates, or to address scholarly and scientific research needs or findings." Priority resources with a geologic connection at the park include "landforms and geologic faults" and "views" (NPS 2019). The following are components of these priority resources: faults, paleontological resources, pinnacles geology, soils, sediments, the Pinnacles Volcanic Formation, and views from or of geologic features.

According to the RSS, the following issues/stressors/threats have the potential to negatively impact natural geologic features and processes in the park:

- Non-native/invasive plants and animals
- Regional development and surrounding land use
- Land management on private lands surrounding the park
- Park development
- Social trail; denudation near campground
- Vandalism, looting, and theft
- Changing fire regimes
- Climate change; precipitation; extreme storms
- Air pollution; pollutant deposition

Seismicity and Earthquakes

A large magnitude earthquake will almost certainly affect the park in the next century. Pinnacles National Park is in an area considered "highest hazard" for earthquake shaking based on the 2018 update of the long-term (next 50 years) National Seismic Hazard Model (fig. 25). The "Richter magnitude" is a well-known measure of the energy released by an earthquake. The "moment magnitude" scale is a more uniformly applicable scale that gives the most reliable estimate of earthquake size and can be estimated from seismographs. Earthquakes can directly damage park infrastructure or trigger other hazards such as slope movements that may impact park resources, infrastructure, or visitor safety.

Earthquakes cannot be prevented, and prediction is imprecise; therefore, preparation is important to minimize the risks associated with earthquake hazards (i.e., destruction of structures or resources due to shaking, creep, surface rupture liquefaction, or landslides). Risk is the probability of occurrence combined with the expected degree of damage or loss that may occur with exposure to a hazard (Holmes et al. 2013). Assuming equal strong shaking during a damaging earthquake, risk is highest in areas where visitation is high, and in and near structures or features susceptible to damage by hazards. The *Geological Monitoring* (Young and Norby 2009) chapter on seismic activity (Braile 2009) provides more information about monitoring seismicity.

The active stretch of the San Andreas Fault nearest the park is now a creeping section and does not generate much shaking. Major earthquakes are less likely to occur, and shaking hazards are lower, here than along locked sections of the fault (e.g., Point Reyes National Seashore; see Port 2018). However, shaking from large earthquakes generated north of and near San Juan Batista or south of and near Parkfield would be strong enough to be felt in the park (Troost 2003). Offset of sidewalks in the nearby town of Hollister (see fig. 21), and of streams in the park, are evidence of ongoing fault creep. Even moderate shaking in the park is significant enough to initiate rockfall. After every earthquake that is felt in the park, park staff examines the caves to identify high risk areas for rockfall (see "Slope Movements").

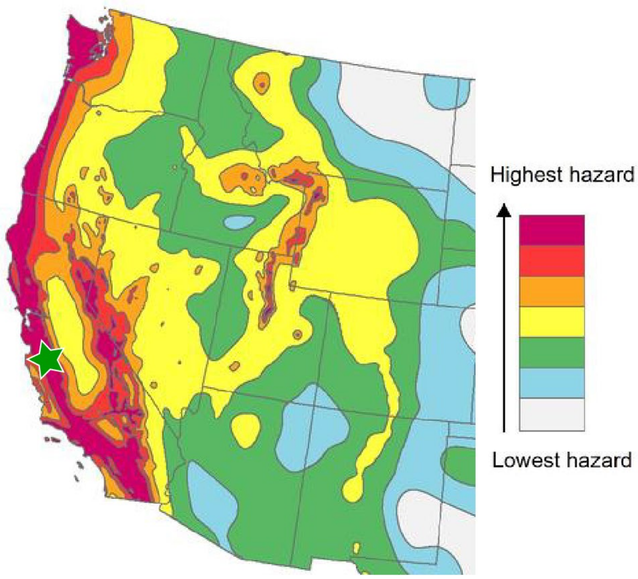

Figure 25. Seismic hazard map of the western United States.
The map shows predicted earthquake hazards across the western United States for the next 50 years based on the 2018 update of the National Seismic Hazard Models (https://www.usgs.gov/programs/earthquake-hazards/science/introduction-national-seismic-hazard-maps). The location of the park is marked with a star. Although the park is adjacent to the "creeping" section of the San Andreas Fault and shaking hazards are lower than by the "locked" sections, small to moderate earthquakes are frequently observed in the park and can trigger rockfall. Graphic modified from the US Geological Survey seismic hazard map (https://www.usgs.gov/media/images/2018-long-term-national-seismic-hazard-map).

Scenarios

Earthquake scenarios describe the expected ground motions and effects of specific hypothetical large earthquakes. An earthquake scenario represents one realization of a potential future earthquake by assuming a particular magnitude, location, and fault-rupture geometry and estimating shaking using a variety of strategies. In planning and coordinating emergency response, utilities, local government, and other organizations are best served by conducting training exercises based on realistic earthquake situations—ones like those they are most likely to face. ShakeMap scenario earthquakes can fill this role. They can also be used to examine exposure of structures, lifelines, utilities, and transportation corridors to specified potential earthquakes.

ShakeMaps are a US Geological Survey product which provides near-real-time maps of ground motion and shaking intensity following significant earthquakes. The ShakeMap website, https://earthquake.usgs.gov/data/shakemap/, provides more information. A ShakeMap earthquake scenario is a predictive ShakeMap. The 2017 collection of nearly 800 ShakeMap earthquake scenarios is the authoritative US Geological Survey collection for the continental US. The scenario fault ruptures are derived from the 2014 update to the National Seismic Hazard Model for the US (Petersen et al. 2014). The collection of events is known as the 2014 Building Seismic Safety Council catalog (available at https://earthquake.usgs.gov/scenarios/catalog/) includes scenarios along the San Andreas Fault to the southeast of the park and other regional faults.

Cave Management

Caves are an irreplaceable part of our nation's geologic heritage, and the caves at Pinnacles are particularly distinct for being talus, rather than dissolution, caves. Management of caves is important because (1) conditions in caves (generally dry and cool) can preserve records of animal and human activity (Santucci et al. 2001), (2) is required by law (the Federal Cave Resource Protection Act of 1988; see "Guidance for Geologic Resource Management"), and (3) caves provide subterranean habitat for many species, some of which are wholly dependent on caves to survive. GRD partners with the National Cave and Karst Research Institute (NCKRI) to monitor and provide management guidance regarding caves on NPS lands. Other cave resources are protected by not sharing information about them publicly.

Management of the talus caves at Pinnacles National Park is primarily a matter of managing habitat for several species of bat. A cave management plan for Bear Gulch established seasonal closures to protect sensitive species including Townsend's big-eared bats (Babalis 2009). After the colony was discovered in 1997, their behavior was studied in order to create seasonal guidelines for accessing the cave and avoiding human disturbance to the colony (NPS 2011).

Bat populations in the park are declining as of 2006; this is likely due to direct and indirect human impacts, primarily through destruction of foraging and roosting sites (NPS 2006a). Townsend's big-eared bats are especially sensitive because they roost on the walls and ceilings rather than tucked away in cracks and crevices (NPS 2011). In 2004, bat gates were installed to prevent human entry and isolate some sections exclusively for bat roosting (fig. 26); a new 200-ft section of trail was built to facilitate these closures (KellerLynn 2008; Babalis 2009). The cave is now normally closed completely from mid-May through mid-July, and partially for most of the remainder of the year, to allow bats to raise their young (NPS 2006a).

Figure 26. Photograph of a bat gate in a talus cave. Bat gates allow flying bats to enter and exit a cave but prevent human visitors from doing so. This allow bats to roost, mate, and raise their young without disturbance. Photograph by Rebecca Port (National Park Service).

In addition to disturbing bats, visitor traffic through the caves is probably having some level of disturbance on invertebrates that inhabit the caves. Baker et al. (2015) provided a framework for inventorying and monitoring cave ecology. It is intended to be a guiding document that outlines what is possible, how to decide what steps to take, and what is already being done. Topics include overview of NPS cave ecosystem management practices; potential monitoring targets; and general guidance for inventorying and monitoring cave ecology. The chapter on caves and associated landscapes (Toomey 2009) in *Geological Monitoring* (Young and Norby 2009) may also be a useful resource.

Flooding

Flooding at the park is a natural process caused by heavy rains. For thousands of years, flooding has shaped the landscape and maintained specific habitats for diverse populations of plants and wildlife. Many park species would exist rarely or not at all if it was not for natural flooding supporting habitat in stream channels and flood plains (Davis et al. 2013).

However, flooding can threaten park resources, facilities, and visitor safety. There have been three significant floods in the Chalone Creek watershed over the past 40 years, including a 40-year flood (a flood with a 40-year return interval) in 1998 (Davis et al. 2013) which inundated 400 linear ft (122 m) of the floodplain. Damage from this flood was attributed to the presence of roads and levees in the flood plain which channelized the stream and prevented it from accessing its flood plain, increasing its energy which was then unleased on downstream areas. Since the 1998 flood, on the east side of the park three bridges have been removed and two bridges have been replaced with designs less likely to cause stream impacts. On the west side of the park, facilities that were in the floodplain were replaced and their former locations are being restored (NPS 2015). A campground on the west side of the park was heavily damaged by flooding in the 1980s and was eventually abandoned. The site is now a day-use picnic area (Timothy Babalis, Pinnacles National Park, Cultural Resources Program Manager, written communication, 7 April 2022).

The talus caves are formed in narrow gorges and they and their associated trails are susceptible to flooding. Rogers (2005) noted that the 1997–98 El Nino floods "significantly altered" the character of Bear Gulch and Balconies Caves, washing away the unconsolidated sand and gravel that had floored the "Inner Sanctum" area of Bear Gulch Caves and leaving a floor of smooth bedrock. Areas of the cave that were above the flood level have remained "dusty." In the Balconies Caves, a thin roof with "skylight" windows over "Lake Hall" was washed away completely, leaving a much larger chamber.

The foundation document recommended a plan that would remove facilities "from riparian areas and the floodplain to restore those areas and to improve safety and maintenance in the long term" (NPS 2015, p. 20). The general management plan (NPS 2013) recommends avoiding development in regulatory floodplains, typically the 100-year floodplain. Participants on the 2018 conference call (see "Acknowledgements") mentioned that the park is in the beginning stages of developing a plan for the east side of the park; however, the FEMA floodplain maps are not adequate for decision making and wetlands restoration at the park level. As of April 2022, this planning effort was recently restarted and is ongoing (Timothy Babalis, written communication, 7 April 2022).

Climate Change

Although climate change planning is beyond the scope of this GRI report, a discussion of climate change is included because of the potential disruption it may cause to the park's geologic resources. Park managers are directed to the NPS Climate Change Response Program (https://www.nps.gov/orgs/ccrp/index.htm) to address climate change planning, which helps park managers develop plausible science-based scenarios that inform strategies and adaptive management activities that allow mitigation or adjustment to climate realities.

Possible outcomes of climate change at the park include (1) oscillation of severe weather and subsequent impacts on the magnitude of flooding and number of debris flows; (2) latitudinal shifts in weather patterns impacting vegetation; and (3) impacts on flora and the associated repercussion of debris flows and flooding (i.e., removal of vegetation destabilizes loose sediment) (KellerLynn 2008).

A nearly 100-year rainfall record shows that, while the "rainy season" has shortened, the overall annual trend is toward a slight increase in precipitation indicating an increase in more intense rainfall events. Park managers are examining a 500-year tree ring record from blue oaks, which may provide a high-resolution record of El Nino events.

Pinnacles National Park is an official member park of the Climate Friendly Parks Program (https://www.nps.gov/subjects/climatechange/cfpprogram.htm), indicating an effort to meet the following goals:

- Measure park-based greenhouse gas emissions.
- Educate staff, partners, stakeholders, and the public about climate change and demonstrate ways individuals and groups can take action to address the issue.
- Assist parks in developing strategies and specific actions to address sustainably challenges, reduce greenhouse gas emissions, and anticipate the impacts of climate change on park resources.

Slope Movements

Slope movements are the gravity-driven transfer of soil, regolith, and/or rock down an incline. Soil creep, rockfalls, debris flows, and avalanches are some common types of slope movements. These processes and the resultant deposits are also known as "mass wasting" and commonly grouped as "landslides." Slope movements occur on time scales ranging from seconds to years (fig. 27). Storms and seismic activity provide ample triggering mechanisms for sudden landslides and rockfall.

According to an unpublished report by Troost (2003), the most active slope movement process in the park is shallow debris sliding. Troost (2003) identified and mapped over 1,100 unstable slopes in the park, which were principally categorized under three main types of slope movement processes: rockfall, rockslides, and debris/earth slides. These processes are most often triggered by rainfall or earthquakes. More than 80% of documented shallow debris and earth slides occurred in the Bickmore Canyon Arkose (**Mlbc**), east of the Chalone Creek fault. All the rockslides in the park that were documented by Troost (2003) occurred west of the Chalone Creek fault, in the Pinnacles Volcanic Formation (**MIOLp** units).

Slope deposits in the park include GRI GIS map unit **Qls** and a GRI GIS data layer ("Landslide Direction Arrows") which indicates direction of slope movements. The regional map (PINN dataset) only maps landslide direction in the Monterey quadrangle (Wagner et al. 2002 source map).I In the San Andreas Fault area of this quadrangle, landslides have occurred where hills consisting of poorly consolidated gravel and sand (Rymer et al. 2006) are eroding and sliding faster than vegetation can take root and stabilize them (Matthews and Webb 1982; see GRI poster). The Pinnacles Volcanic Formation map (PIVF dataset) includes landslide directions within the park. The GRI GIS data, however, is not a comprehensive landslide inventory—other landslides may exist that were not detected because of the extents and scales of the source maps compiled for the GRI GIS data (see "GRI Products").

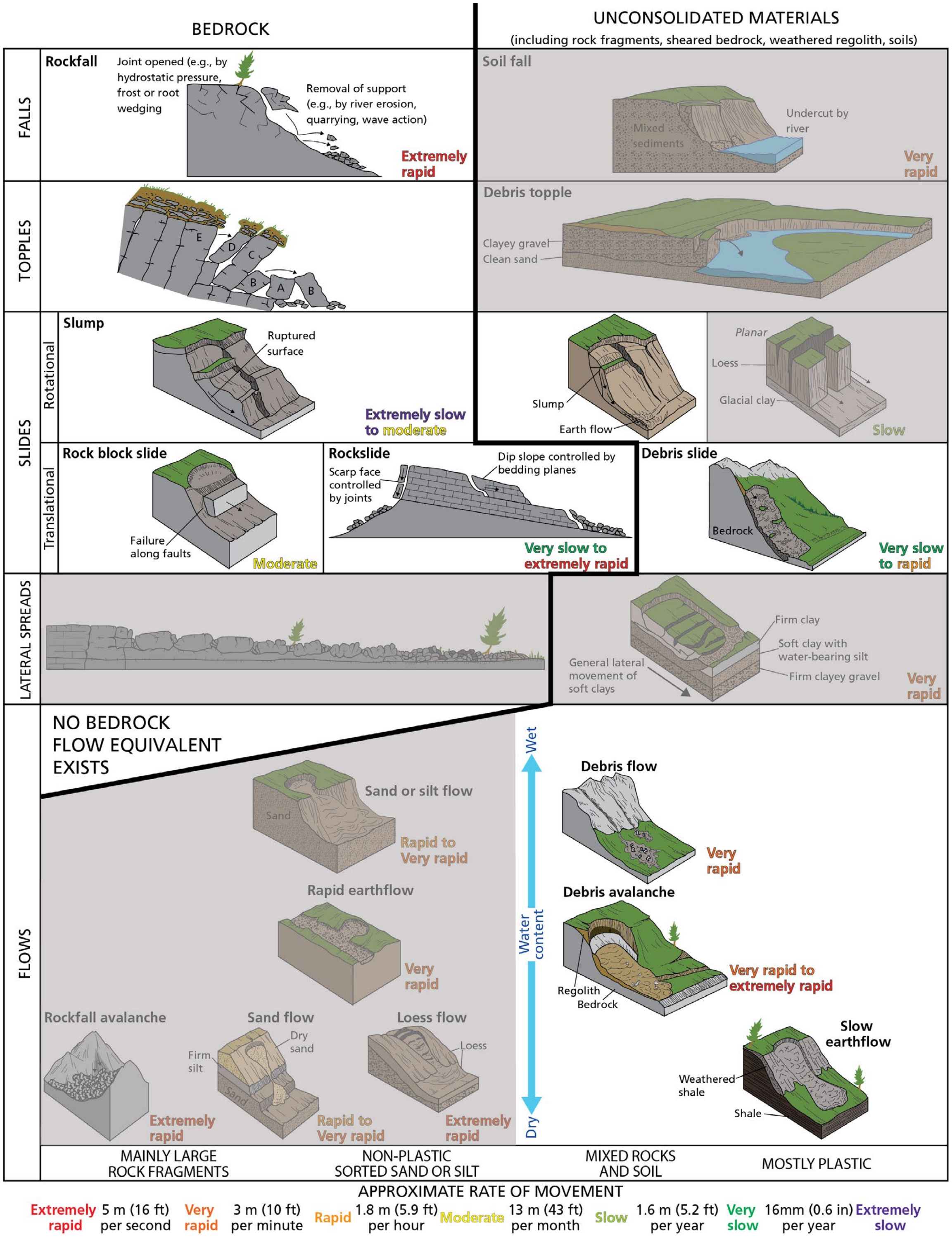

Figure 27. Diagram of different types of slope movement.
Slope movements can occur at all speeds and scales. This diagram shows the different types of slope movements that can occur in different materials. The processes that are not known to occur at the park are greyed out. The park has evidence of over 1,000 occurrences of slope movement, as mapped in the GRI GIS data and by Troost (2003). These fall into the primary categories of rockfalls, rockslides, and debris/earth slides. These processes are most often triggered by rainfall, earthquakes, and strong weathering processes. Factors that determine how slope movements occur include the size and cohesiveness of the moving mass, the amount of water present, and any triggering event such as an earthquake. Graphic by Trista Thornberry-Ehrlich (Colorado State University) redrafted after a graphic and information in Varnes (1978) and Cruden and Varnes (1996).

Slope movements are responsible for shaping the landscape preserved in the park, especially the talus caves. Because slope movements are a natural process, prevention is not a resource management goal. The goal is to "remove and prevent permanent development from hazardous areas so that geologic processes many continue naturally without undue cost and risk to facilities" (Troost 2003, p. 1). Slope movements also have the potential to be hazardous to visitors and park staff. NPS Director's Order #50C Public Risk Management Program (Jarvis 2010) states the NPS "must strive to prevent visitor injuries and fatalities within the limits of available resources. Within this context, visitor risk management does not mean eliminating all dangers, nor can the NPS guarantee visitor safety or be responsible for acts and decisions made by visitors that may result in their injury or illness." NPS Policy Memorandum 15-01 (Jarvis 2015) directs NPS managers and their teams to proactively identify and document facility vulnerabilities to climate change and other natural hazards, which includes mass wasting events and rockfalls.

This report may present recommendations for reducing risks related to slope movements, however, it is up to the discretion of decision-makers at the park level on whether, how, and when to implement these recommendations and will be subject to availability of funding and staffing as well as legal and policy considerations.

Day use areas and park staff residences are in known rockfall hazard areas (GRI conference call participants, 25 January 2018). The greatest hazards in the park come from shallow debris sliding and rockslides at the headquarters area (fig. 28) and rockfall for trail systems (Troost 2003). Landslides are locally abundant along highway 25 where the hills are mantled with poorly consolidated gravel and sand that commonly slide downhill when saturated with water (Rymer et al. 2006).

Visitor safety in caves due to rockfall is a concern. Rock movement in the caves was studied (Troost 2003) and no movement was detected. While the possibility of rockfall injuring a visitor in the caves is recognized, it was not considered a major management concern as

Figure 28. Photograph of mass wasting damage at headquarters building.
This photograph shows an example of the damage to facilities that slope movements can cause, especially when combined with water as in this debris flow in 1998. Photograph from Troost (2003, figure 1).

of the 2018 conference call. Actions to reduce risk of rockfall related injuries in caves could include removing rocks, installing warning signs, and using barricades to reduce access.

Slope movements may also impact vegetation, such as if a rockslide-impounded lake forms which could support growth of trees. Though none of these lakes currently exist, Troost (2003) observed sycamore stands around rockslides within Bear Gulch and Frog Canyon that may have initially grown in connection with a rockslide-impounded lake.

An accurate map of slopes with the potential for failure is important for resource management within the park and for facilities planning. The Unstable Slopes Management Program (USMP) has developed a standardized process to proactively rate unstable slopes for the degree of risk to park assets, staff, and visitors. The USMP is sponsored by Federal Highway Administration (Western Federal Lands), the National Park Service, US Forest Service, and the Bureau of Land Management. Resource managers can work with GRD to incorporate this program in geohazard assessment in the park (see the "Landslides and Slope Movements" section in the "Guidance for Geologic Resource Management" chapter).

Rock Climbing

Pinnacles has more than 900 climbing routes including the front- and backcountry areas and wilderness (NPS 2015). Management of climbing has historically been informal; the Friends of Pinnacles organization (see https://pinnacles.org/) has largely been responsible for managing maintenance and documentation of bolted routes. The relationship between the park and the climbing community has been good and few problems have been documented (NPS 2015). Nevertheless, because bolted routes and guided trips occur in the Hain Wilderness, the park has a responsibility to manage these activities. Human waste can be an issue near climbing areas; no effort has been made to study the impact at this time (NPS 2015). Climbing on the rocks, installing bolts, litter, and human waste all have the potential to degrade geologic and other natural resources (fig. 29). These issues could be addressed in a wilderness stewardship plan or climbing management plan.

In addition to being a popular climbing destination, the rugged pinnacles landscape is an important bird habitat for raptors and the critically endangered California Condor. Working with Friends of Pinnacles, the park uses a voluntary closure model (NPS 2013) in congruence with raptor advisory updates to protect the habitat and maximize the potential of successful nest establishment.

Figure 29. Photograph of a climbing bolt. Climbing bolts, and other traces of climbing activity, can degrade and pollute the wilderness designated areas of Pinnacles National Park. Photograph by Rebecca Port (National Park Service).

Disturbed Lands Restoration

Land recently added to the park (since 2000) contains disturbed lands, or lands where the natural conditions and processes have been impacted by development and/or by agricultural practices, specifically several ponds with earthen dams. At least one of the dams had failed as of 2013, with others near failing (Davis et al. 2013).

Park managers have submitted several technical assistance requests (TARs) for hydrology and watershed management. TARS can be viewed on the Solution for Technical Assistance Requests (STAR) webpage: https://irma.nps.gov/Star/ (available on the Department of the Interior network only). Mike Martin (NPS Water Resources Division, hydrologist) has responded to most of these requests; contact the park for the current status of each project. Projects have included:

- Restoration of a historically dry-farmed valley bottom that has become heavily infested with invasive plants. The invasive species largely displaced native plants, and the resulting dense thatch made the area inhospitable to many prairie species, including the federally threatened California tiger salamander. The park burned the area and followed up with herbicide treatments to practically eliminate invasive yellow star-thistle. Experimental revegetation treatments are currently underway as of 2022. In addition, the hydrology on the flat lands was affected by a culvert and channelization of a stream, and changes to the land contours because of farming (STAR ID 470).
- Rebuilding an earthen dam in Needlegrass Canyon to restore a pond for salamander breeding habitat. The area was grazed by cattle and historically dry-

farmed; it is now (as of 2022) infested with invasive plant species. Human caused erosion needs to be addressed, in particular the formation of a "grand canyon" where the earthen dam failed and is rapidly downcutting (STAR ID 1136). In Rose Canyon, restoration efforts are underway (as of 2022) to protect another California tiger salamander breeding pond from dam failure.

- Restoration of a historic pond at the current site of Moses Spring parking lot. The restored pond could serve as breeding habitat for federally threatened Californian red-legged frogs. Possible solutions range from removing the parking lot and restoring the pond to leaving the parking lot and building a smaller pond nearby. As of 2022, restoration scenarios are being created and evaluated for use as alternatives in NEPA compliance (STAR ID 475).

Groundwater Quality and Springs

To help define baseline water quality of key water resources at Pinnacles National Monument, California, the US Geological Survey collected and analyzed ground water from seven springs sampled during June 2006 (see Borchers and Lyttge 2007). The seven sampled springs are of generally good quality, although three of the springs had dissolved arsenic concentrations that were higher than the US Environmental Protection Agency drinking water standard of 10 µg/L (Borchers and Lyttge 2007). In most cases, the concentrations of measured water-quality constituents in spring samples were lower than California threshold standards for drinking water and Federal threshold standards for drinking water and aquatic life. Water-quality information for samples collected from the springs provided a reference point for comparison of samples collected subsequently by the NPS San Francisco Bay Area Inventory & Monitoring Network (SFAN) and hydrologic studies in the park. See the SFAN website for Pinnacles National Park, https://www.nps.gov/im/sfan/pinn.htm, for a complete list of vital signs monitored at the park and associated reports. These comparisons helped park resource managers assess relations between water chemistry, geology, and land use.

Paleontological Resource Inventory, Monitoring, and Protection

All paleontological resources are nonrenewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act (see "Guidance for Geologic Resource Management"). Several opportunities for paleontological investigations exist or are underway in the park. Russ Graymer and others (Graymer et al. 2018 draft) have been working on a map (in progress as of 2022) which will cover the northeast part of the park and include fossil localities. There is a possibility that paleontological resources could be discovered in the talus caves, although there are no documented occurrences. Mollusk fossils from outside the park are being swept into the park by streams from the north and east; these fossils have not been collected or analyzed by park staff or researchers (GRI conference call participants, 25 January 2018).

The NPS network-level paleontological inventory by Elder et al. (2008) included preliminary recommendations for Pinnacles National Park:

- A field-based investigation to determine the distribution and identity of fossils found within potentially fossiliferous units listed (in the Elder et al. 2008 report).
- Additional research into the ostracodes and potential fossils in the Miocene volcanics (**MIOLp** units) in the park may yield further insight into these uncommon fossil occurrences.
- Paleontology field work could be accomplished by establishing a cooperative agreement with one or more of the dominant natural history museums or the US Geological Survey. The NPS Geologic Resources Division can help advertise, recruit, and provide technical assistance for this work (see "Guidance for Geologic Resource Management").

In addition, Santucci et al. (2009) detailed five methods and vital signs for monitoring in situ paleontological resources: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use.

Oil, Gas, and Mineral Development

The NPS works with adjacent land managers and other permitting entities to help ensure NPS resources and values are not adversely impacted by external mineral exploration and development. Potential impacts include groundwater and surface water contamination, erosion and siltation, introduction of exotic plant species, reduction of wildlife habitat, impairment of viewsheds and night skies, excessive noise, and diminished air quality. Visitor safety and overall degradation of the visitor experience are particular concerns. The NPS Geologic Resources Division Energy and Minerals website, https://go.nps.gov/grd_energyminerals, provides additional information.

Oil is known to occur west of the park in the Salinas Valley. 5,000 to 10,000 ft (1,500 to 3,000 m) of sediment accumulated in this valley when it was below sea level until about 2 million years ago. Oil was discovered at the southern end of the valley, near San Ardo, where it is trapped within layers of permeable sandstone and bound by surrounding fine-grained, impermeable rock. As of 2000, the southern end of the valley is still the only part which produces oil (Alt and Hyndman 2000). In 1951 an exploratory well was drilled in the north of the park, into the undifferentiated Monterey Formation (**Mlm**). The well was drilled to 3700 ft (1128 m) with no signs of hydrocarbons and was promptly plugged and abandoned. The road to the site and the wellsite itself have revegetated since then (Forrest Smith, NPS Geologic Resources Division, petroleum engineer, written communication, 25 April 2022).

In 2013, park staff requested and received technical assistance for *Park Response and Review of Oil and Gas Development Surrounding Pinnacles National Park* (STAR ID 1441). A renewed interest in oil and gas development on private and Bureau of Land Management lands surrounding the park raised concerns about potential consequences to the region's scarce water supply and the recovery program for the California condor. The condors use the surrounding ranch lands to forage, roost, and nest.

Ludington and others (1987) prepared a report presenting the results of a mineral survey of lands which are today part of the national park. Two areas were identified as having any potential (albeit low) for mineral resources: one for gold and silver, the other for diatomite and oil and gas (fig. 30).

Abandoned Mineral Lands

Abandoned mineral lands (AML) are lands, waters, and surrounding watersheds that contain facilities, structures, improvements, and disturbances associated with past mineral exploration, extraction, processing, and transportation, including oil and gas features and operations, for which the NPS takes action under various authorities to mitigate, reclaim, or restore in order to reduce hazards and impacts to resources. A legacy of abandoned mines and oil and gas wells exist in parks posing public safety risks and environmental damage. Management Policies (NPS 2006b) requires the closure and reclamation of abandoned mines within parks.

Historically, mining in the park was not particularly profitable for the prospectors. The mines are now abandoned, except by bats in the Defiance and Crowley mines (KellerLynn 2008; GRI conference call, 25 January 2018). According to the NPS AML database and Burghardt et al. (2014), the park contains 34 AML features across 8 sites related to gold, copper, and uranium mining, and a partially restored perlite quarry. Of those features, 21 are mitigated or require no action and the remaining 13 features need either assessment or mitigation (Kyle Hinds, NPS Geologic Resources Division, mining engineer, written communication, 8 March 2022). AML features pose a host of resource management issues such as visitor and staff safety and environmental quality of air, water, and soil. Participants on the 2018 GRI conference call (see "Acknowledgements") expressed a desire to know if there are pollution concerns associated with abandoned mines in the park; no records of testing could be located. AML features can also provide habitat for bats and other animals, some of which may be protected under the Endangered Species Act or state species listing.

Resources management of AML features requires accurate inventory and reporting. All AML features in NPS units should be recorded in the servicewide AML database. The NPS Geologic Resources Division can assist with inventory of AML features not already identified (see "Guidance for Geologic Resource Management"). The NPS AML website, https://go.nps.gov/aml, provides further information.

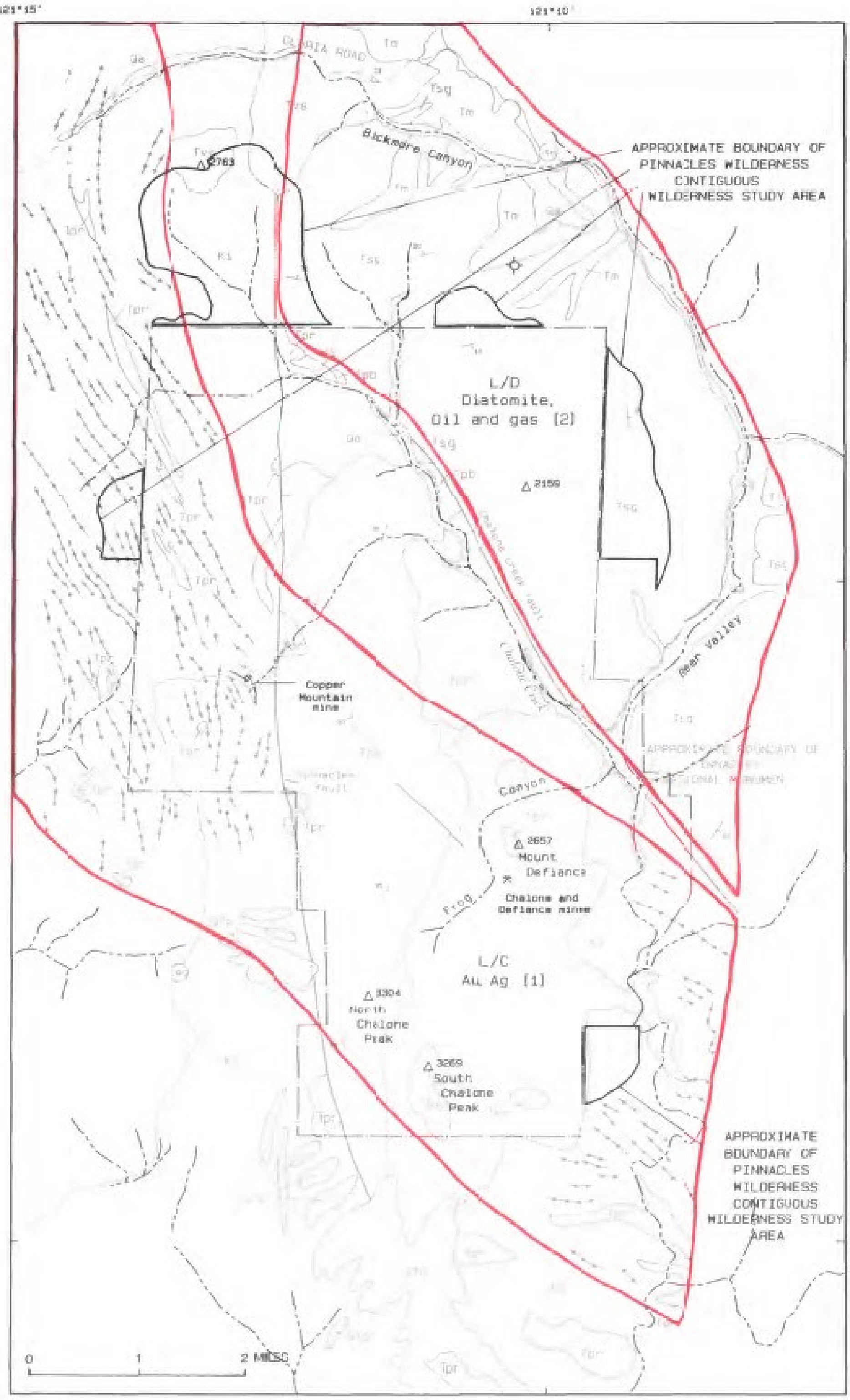

Figure 2. Mineral resource potential and generalized geology of the Pinnacles Wilderness Contiguous Wilderness Study Area, Monterey and San Benito Counties, California. Geology modified from Dibblee (1971, 1975).

Figure 30. Map of areas with mineral potential in Pinnacles National Park.
Two areas in the park were determined to have low mineral potential (Ludington et al. 1987). The two areas are shown outlined in red. The area on the west side of the park has low potential for gold and silver. The area on the east side of the park has low potential for diatomite, and oil and gas resources. Figure from Ludington et al. (1987, figure 2).

Guidance for Geologic Resource Management

Information in this chapter will assist resource managers in addressing geologic resource management issues and applying NPS policy. The laws, regulations, and policies apply to NPS geologic resources. The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (§ 204), National Park Service 2006 Management Policies, and the Natural Resources Inventory and Monitoring Guideline (NPS-75).

Access to GRI Products

- GRI products (scoping summaries, GIS data, posters, and reports): http://go.nps.gov/gripubs
- GRI products are also available through the NPS Integrated Resource Management Applications (IRMA) portal: https://irma.nps.gov/. Enter "GRI" as the search text and select a park from the unit list.
- Additional information regarding the GRI, including contact information: https://www.nps.gov/subjects/geology/gri.htm

Four Ways to Receive Geologic Resource Management Assistance

- Contact the NPS Geologic Resources Division (https://www.nps.gov/orgs/1088/contactus.htm). GRD staff members provide coordination, support, and guidance for geologic resource management issues in three emphasis areas: (1) geologic heritage, (2) active processes and hazards, and (3) energy and minerals management. GRD staff can provide technical assistance with resource inventories, assessments and monitoring; impact mitigation, restoration, and adaptation; hazards risk management; laws, regulations, and compliance; resource management planning; and data and information management. Park managers can formally request assistance via https://irma.nps.gov/Star/.
- Formally request assistance at the Solution for Technical Assistance Requests (STAR) webpage: https://irma.nps.gov/Star/ (available on the Department of the Interior [DOI] network only). NPS employees (from a park, region, or any other office outside of the Natural Resource Stewardship and Science [NRSS] Directorate) can submit a request for technical assistance from NRSS divisions and programs.
- Submit a proposal to receive geologic expertise through the Scientists in Parks (SIP; see https://www.nps.gov/subjects/science/scientists-in-parks.htm). Formerly the Geoscientists-in-the-Parks program, the SIP program places scientists (typically undergraduate students) in parks to complete science-related projects that may address resource management issues. Proposals may be for assistance with research, interpretation and public education, inventory, and/or monitoring. The Geologic Resources Division can provide guidance and assistance with submitting a proposal. The Geological Society of America and Environmental Stewards are partners of the SIP program.
- Refer to *Geological Monitoring* (Young and Norby 2009), which provides guidance for monitoring vital signs (measurable parameters of the overall condition of natural resources). Each chapter covers a different geologic resource and includes detailed recommendations for resource managers, suggested methods of monitoring, and case studies. Chapters are available online at https://www.nps.gov/subjects/geology/geological-monitoring.htm.

Assistance with other Natural Resource Issues

Some of the issues discussed in this report (e.g., stream and wetlands monitoring, responding to climate change) have geological connections but are more suited to receiving assistance from other division of NRSS. Information about these divisions, including contact information, can be found at the following websites:

- Natural Resource Stewardship and Science Directorate: https://www.nps.gov/orgs/1778/index.htm
- Water Resources Division: https://www.nps.gov/orgs/1439/index.htm
- Climate Change Response Program: https://www.nps.gov/orgs/ccrp/index.htm
- Environmental Quality Division: https://www.nps.gov/orgs/1812/index.htm

Pinnacles National Park Documents

The park's foundation document (NPS 2015), general management plan and environmental assessment (NPS 2013), and resource stewardship strategy (NPS 2019) are primary sources of information for resource management within the park.

NPS Resource Management Guidance and Documents

- NPS Management Policies 2006 (Chapter 4: Natural Resource Management): https://www.nps.gov/policy/index.cfm
- National Parks Omnibus Management Act of 1998: https://www.congress.gov/bill/105th-congress/senate-bill/1693
- Natural Resources Inventory and Monitoring Guideline (NPS-75): https://irma.nps.gov/DataStore/Reference/Profile/622933
- Natural Resource Management Reference Manual #77 (NPS-77): https://irma.nps.gov/DataStore/Reference/Profile/572379
- Resist-Accept-Direct (RAD)—A Framework for the 21st-Century Natural Resource Manager: https://doi.org/10.36967/nrr-2283597

Geologic Resource Laws, Regulations, and Policies

The following table (table 9), which was developed by the NPS Geologic Resources Division, summarizes laws, regulations, and policies that specifically apply to NPS minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available.

Table 9. Geologic resource laws, regulations, and policies

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Paleontology	**Archaeological Resources Protection Act of 1979, 16 USC §§ 470aa – mm Section 3 (1) Archaeological Resource—**nonfossilized and fossilized paleontological specimens, or any portion or piece thereof, shall not be considered archaeological resources, under the regulations of this paragraph, unless found in an archaeological context. Therefore, fossils in an archaeological context are covered under this law. **Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309 Section 3 (5) Cave Resource—**the term “cave resource” includes any material or substance occurring naturally in caves on Federal lands, such as animal life, plant life, paleontological deposits, sediments, minerals, speleogens, and speleothems. Therefore, every reference to cave resource in the law applies to paleontological resources. **National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa et seq.** provides for the management and protection of paleontological resources on federal lands.	**36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted. **43 CFR Part 49** (in development) will contain the DOI regulations implementing the Paleontological Resources Preservation Act.	**Section 4.8.2 requires NPS to protect geologic features from adverse effects of human activity.** **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.

Table 9, continued. Geologic resource laws, regulations, and policies.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/ Agriculture to identify "significant caves" on Federal lands, regulate/ restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester. **National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of cave and karst resources. **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be cancelled with appropriate compensation; and lands are withdrawn from mineral entry.	**36 CFR § 2.1** prohibits possessing/ destroying/ disturbing…cave resources…in park units. **43 CFR Part 37** states that all NPS caves are "significant" and sets forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2 requires NPS to protect geologic features from adverse effects of human activity.** **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.
Recreational Collection of Rocks Minerals	**NPS Organic Act, 54 USC. § 100101 et seq.** directs the NPS to conserve all resources in parks (which includes rock and mineral resources) unless otherwise authorized by law. **Exception: 16 USC. § 445c (c) – Pipestone National Monument enabling statute**. Authorizes American Indian collection of catlinite (red pipestone).	**36 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources… in park units. **Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown. **Exception: 36 C.F.R. § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, and Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.

Table 9, continued. Geologic resource laws, regulations, and policies.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Soils	**Soil and Water Resources Conservation Act, 16 USC §§ 2011–2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources. **Farmland Protection Policy Act, 7 USC § 4201 et. seq.** requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).	**7 CFR Parts 610 and 611** are the US Department of Agriculture regulations for the Natural Resources Conservation Service. **Part 610** governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. **Part 611** governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements.	**Section 4.8.2.4** requires NPS to -prevent unnatural erosion, removal, and contamination; -conduct soil surveys; -minimize unavoidable excavation; and -develop/follow written prescriptions (instructions).

Table 9, continued. Geologic resource laws, regulations, and policies.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Geothermal	**Geothermal Steam Act of 1970, 30 USC. § 1001 et seq.** as amended in 1988, states -No geothermal leasing is allowed in parks. -"Significant" thermal features exist in 16 park units (the features listed by the NPS at 52 Fed. Reg. 28793-28800 (August 3, 1987), plus the thermal features in Crater Lake, Big Bend, and Lake Mead). -NPS is required to monitor those features. -Based on scientific evidence, Secretary of Interior must protect significant NPS thermal features from leasing effects. **Geothermal Steam Act Amendments of 1988, Public Law 100--443** prohibits geothermal leasing in the Island Park known geothermal resource area near Yellowstone and outside 16 designated NPS units if subsequent geothermal development would significantly adversely affect identified thermal features.		**Section 4.8.2.3** requires NPS to -Preserve/maintain integrity of all thermal resources in parks. -Work closely with outside agencies. -Monitor significant thermal features.

Table 9, continued. Geologic resource laws, regulations, and policies.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Mining Claims (Locatable Minerals)	**Mining in the Parks Act of 1976, 54 USC § 100731 et seq.** authorizes NPS to regulate all activities resulting from exercise of mineral rights, on patented and unpatented mining claims in all areas of the System, in order to preserve and manage those areas. **General Mining Law of 1872, 30 USC § 21 et seq.** allows US citizens to locate mining claims on Federal lands. Imposes administrative and economic validity requirements for "unpatented" claims (the right to extract Federally-owned locatable minerals). Imposes additional requirements for the processing of "patenting" claims (claimant owns surface and subsurface). Use of patented mining claims may be limited in Wild and Scenic Rivers and OLYM, GLBA, CORO, ORPI, and DEVA. **Surface Uses Resources Act of 1955, 30 USC § 612** restricts surface use of unpatented mining claims to mineral activities.	**36 CFR § 5.14** prohibits prospecting, mining, and the location of mining claims under the general mining laws in park areas except as authorized by law. **36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart A** requires the owners/operators of mining claims to demonstrate bona fide title to mining claim; submit a plan of operations to NPS describing where, when, and how; prepare/submit a reclamation plan; and submit a bond to cover reclamation and potential liability. **43 CFR Part 36** governs access to mining claims located in, or adjacent to, National Park System units in Alaska.	**Section 6.4.9** requires NPS to seek to remove or extinguish valid mining claims in wilderness through authorized processes, including purchasing valid rights. Where rights are left outstanding, NPS policy is to manage mineral-related activities in NPS wilderness in accordance with the regulations at **36 CFR Parts 6** and **9A**. **Section 8.7.1** prohibits location of new mining claims in parks; requires validity examination prior to operations on unpatented claims; and confines operations to claim boundaries.
Nonfederal Oil and Gas	**NPS Organic Act, 54 USC § 100751 et seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). Individual Park Enabling Statutes: **16 USC § 230a** (Jean Lafitte NHP & Pres.) **16 USC §450kk** (Fort Union NM), **16 USC § 459d-3** (Padre Island NS), **16 USC § 459h-3** (Gulf Islands NS), **16 USC § 460ee** (Big South Fork NRRA), **16 USC § 460cc-2(i)** (Gateway NRA), **16 USC § 460m** (Ozark NSR), **16 USC§698c** (Big Thicket N Pres.), **16 USC §698f** (Big Cypress N Pres.)	**36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart B** requires the owners/operators of nonfederally owned oil and gas rights outside of Alaska to -demonstrate bona fide title to mineral rights; -submit an Operations Permit Application to NPS describing where, when, how they intend to conduct operations; -prepare/submit a reclamation plan; and -submit a bond to cover reclamation and potential liability. **43 CFR Part 36** governs access to nonfederal oil and gas rights located in, or adjacent to, National Park System units in Alaska.	**Section 8.7.3** requires operators to comply with 9B regulations.

Table 9, continued. Geologic resource laws, regulations, and policies.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Federal Mineral Leasing (Oil, Gas, and Solid Minerals)	**The Mineral Leasing Act, 30 USC § 181 et seq.**, and the **Mineral Leasing Act for Acquired Lands, 30 USC § 351 et seq.** do not authorize the BLM to lease federally owned minerals in NPS units. **Combined Hydrocarbon Leasing Act, 30 USC §181,** allowed owners of oil and gas leases or placer oil claims in Special Tar Sand Areas (STSA) to convert those leases or claims to combined hydrocarbon leases, and allowed for competitive tar sands leasing. This act did not modify the general prohibition on leasing in park units but did allow for lease conversion in GLCA, which is the only park unit that contains a STSA. **Exceptions**: Glen Canyon NRA (**16 USC § 460dd et seq.**), Lake Mead NRA (**16 USC § 460n et seq.**), and Whiskeytown-Shasta-Trinity NRA (**16 USC § 460q et seq.**) authorizes the BLM to issue federal mineral leases in these units provided that the BLM obtains NPS consent. Such consent must be predicated on an NPS finding of no significant adverse effect on park resources and/or administration. **American Indian Lands Within NPS Boundaries Under the Indian Allottee Leasing Act of 1909, 25 USC §396, and the Indian Leasing Act of 1938, 25 USC §396a, §398 and §399, and Indian Mineral Development Act of 1982, 25 USCS §§2101-2108,** all minerals on American Indian trust lands within NPS units are subject to leasing. **Federal Coal Leasing Amendments Act of 1975, 30 USC § 201** prohibits coal leasing in National Park System units.	**36 CFR § 5.14** states prospecting, mining, and… leasing under the mineral leasing laws [is] prohibited in park areas except as authorized by law. **BLM regulations at 43 CFR Parts 3100, 3400, and 3500** govern Federal mineral leasing. **Regulations re: Native American Lands within NPS Units:** **25 CFR Part 211** governs leasing of tribal lands for mineral development. **25 CFR Part 212** governs leasing of allotted lands for mineral development. **25 CFR Part 216** governs surface exploration, mining, and reclamation of lands during mineral development. **25 CFR Part 224** governs tribal energy resource agreements. **25 CFR Part 225** governs mineral agreements for the development of Indian-owned minerals entered into pursuant to the **Indian Mineral Development Act of 1982, Pub. L. No. 97-382, 96 Stat. 1938** (codified at **25 USC §§ 2101-2108**). **30 CFR §§ 1202.100-1202.101** governs royalties on oil produced from Indian leases. **30 CFR §§ 1202.550-1202.558** governs royalties on gas production from Indian leases. **30 CFR §§ 1206.50-1206.62** and **§§ 1206.170-1206.176** governs product valuation for mineral resources produced from Indian oil and gas leases. **30 CFR § 1206.450** governs the valuation coal from Indian Tribal and Allotted leases. **43 CFR Part 3160** governs onshore oil and gas operations, which are overseen by the BLM.	**Section 8.7.2** states that all NPS units are closed to new federal mineral leasing except Glen Canyon, Lake Mead and Whiskeytown-Shasta-Trinity NRAs.

Table 9, continued. Geologic resource laws, regulations, and policies.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Nonfederal minerals other than oil and gas	**NPS Organic Act, 54 USC §§ 100101 and 100751**	**NPS regulations at 36 CFR Parts 1, 5, and 6** require the owners/operators of other types of mineral rights to obtain a special use permit from the NPS as a **§ 5.3** business operation, and **§ 5.7** – Construction of buildings or other facilities, and to comply with the solid waste regulations at **Part 6**.	**Section 8.7.3** states that operators exercising rights in a park unit must comply with **36 CFR Parts 1** and **5**.
Coal	**Surface Mining Control and Reclamation Act of 1977, 30 USC § 1201 et. seq.** prohibits surface coal mining operations on any lands within the boundaries of a NPS unit, subject to valid existing rights.	**SMCRA Regulations at 30 CFR Chapter VII** govern surface mining operations on Federal lands and Indian lands by requiring permits, bonding, insurance, reclamation , and employee protection. **Part 7** of the regulations states that National Park System lands are unsuitable for surface mining.	None Applicable.
Uranium	**Atomic Energy Act of 1954:** Allows Secretary of Energy to issue leases or permits for uranium on BLM lands; may issue leases or permits in NPS areas only if president declares a national emergency.	None Applicable.	None Applicable.

Table 9, continued. Geologic resource laws, regulations, and policies.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Climate Change	**Secretarial Order 3289** (Addressing the Impacts of Climate Change on America's Water, Land, and Other Natural and Cultural Resources) (2009) requires DOI bureaus and offices to incorporate climate change impacts into long-range planning; and establishes DOI regional climate change response centers and Landscape Conservation Cooperatives to better integrate science and management to address climate change and other landscape scale issues. **Executive Order 13693** (Planning for Federal Sustainability in the Next Decade) (2015) established to maintain Federal leadership in sustainability and greenhouse gas emission reductions.	None Applicable.	**Section 4.1** requires NPS to investigate the possibility to restore natural ecosystem functioning that has been disrupted by past or ongoing human activities. This would include climate change, as put forth by Beavers et al. (in review). **Policy Memo 12-02** (Applying National Park Service Management Policies in the Context of Climate Change) (2012) applies considerations of climate change to the impairment prohibition and to maintaining "natural conditions". **Policy Memo 14-02** (Climate Change and Stewardship of Cultural Resources) (2014) provides guidance and direction regarding the stewardship of cultural resources in relation to climate change. **Policy Memo 15-01** (Climate Change and Natural Hazards for Facilities) (2015) provides guidance on the design of facilities to incorporate impacts of climate change adaptation and natural hazards when making decisions in national parks.

Table 9, continued. Geologic resource laws, regulations, and policies.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Common Variety Mineral Materials (Sand, Gravel, Pumice, etc.)	**Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units. **Reclamation Act of 1939, 43 USC §387**, authorizes removal of common variety mineral materials from federal lands in federal reclamation projects. This act is cited in the enabling statutes for Glen Canyon and Whiskeytown National Recreation Areas, which provide that the Secretary of the Interior may permit the removal of federally owned nonleasable minerals such as sand, gravel, and building materials from the NRAs under appropriate regulations. Because regulations have not yet been promulgated, the National Park Service may not permit removal of these materials from these National Recreation Areas. **16 USC §90c-1(b)** authorizes sand, rock and gravel to be available for sale to the residents of Stehekin from the non-wilderness portion of Lake Chelan National Recreation Area, for local use as long as the sale and disposal does not have significant adverse effects on the administration of the national recreation area.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: -only for park administrative uses; -after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment; -after finding the use is park's most reasonable alternative based on environment and economics; -parks should use existing pits and create new pits only in accordance with park-wide borrow management plan; -spoil areas must comply with **Part 6** standards; and -NPS must evaluate use of external quarries. Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director.

Table 9, continued. Geologic resource laws, regulations, and policies.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Coastal Features and Processes	**NPS Organic Act, 54 USC § 100751 et. seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). **Coastal Zone Management Act, 16 USC § 1451 et. seq.** requires Federal agencies to prepare a consistency determination for every Federal agency activity in or outside of the coastal zone that affects land or water use of the coastal zone. **Clean Water Act, 33 USC § 1342/ Rivers and Harbors Act, 33 USC 403** require that dredge and fill actions comply with a Corps of Engineers Section 404 permit. **Executive Order 13089** (coral reefs) (1998) calls for reduction of impacts to coral reefs. **Executive Order 13158** (marine protected areas) (2000) requires every federal agency, to the extent permitted by law and the maximum extent practicable, to avoid harming marine protected areas.	**36 CFR § 1.2(a)(3)** applies NPS regulations to activities occurring within waters subject to the jurisdiction of the US located within the boundaries of a unit, including navigable water and areas within their ordinary reach, below the mean high water mark (or OHW line) without regard to ownership of submerged lands, tidelands, or lowlands. **36 CFR § 5.7** requires NPS authorization prior to constructing a building or other structure (including boat docks) upon, across, over, through, or under any park area.	**Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.8.1** requires NPS to allow natural geologic processes to proceed unimpeded. NPS can intervene in these processes only when required by Congress, when necessary for saving human lives, or when there is no other feasible way to protect other natural resources/ park facilities/historic properties. **Section 4.8.1.1** requires NPS to: -Allow natural processes to continue without interference, -Investigate alternatives for mitigating the effects of human alterations of natural processes and restoring natural conditions, -Study impacts of cultural resource protection proposals on natural resources, -Use the most effective and natural-looking erosion control methods available, and -Avoid putting new developments in areas subject to natural shoreline processes unless certain factors are present.

Table 9, continued. Geologic resource laws, regulations, and policies.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Upland and Fluvial Processes	**Rivers and Harbors Appropriation Act of 1899, 33 USC § 403** prohibits the construction of any obstruction on the waters of the United States not authorized by congress or approved by the USACE. **Clean Water Act 33 USC § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US [including streams]). **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also **D.O. 77-2**) **Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also **D.O. 77-1)**	None applicable.	**Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems. **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks, unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding. **Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human-caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams. **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include…erosion and sedimentation…processes. **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.

Additional References, Resources, and Websites

California Geology

- California Geological Survey: https://www.conservation.ca.gov/cgs

Climate Change Resources

- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/
- NPS Climate Change Response Program Resources: http://www.nps.gov/subjects/climatechange/resources.htm
- NPS Sea Level Rise Map Viewer: https://maps.nps.gov/slr/
- NPS Policy Memorandum 15-01 Addressing Climate Change and Natural Hazards for Facilities: https://npspolicy.nps.gov/PolMemos/policymemoranda.htm
- NPS Climate Change, Sea Level Change website: https://www.nps.gov/subjects/climatechange/sealevelchange.htm/index.htm
- US Global Change Research Program: http://www.globalchange.gov/home

Earthquakes

- California Geological Survey, earthquakes: https://www.conservation.ca.gov/cgs/geologic_hazards/earthquakes
- ShakeAlert: An Earthquake Early Warning System for the West Coast of the United States (USGS sponsored): https://www.shakealert.org/
- USGS Earthquake Hazards Program unified hazard tool: https://earthquake.usgs.gov/hazards/interactive/
- *The California earthquake of April 18, 1906* (Lawson 1908)
- *The mechanics of the earthquake, the California earthquake of April 18, 1906* (Reid 1910)
- *Uniform California earthquake rupture forecast, version 3 (UCERF3)—The time-independent model* (Field et al. 2013)

Geologic Heritage

- NPS America's Geologic Heritage: https://www.nps.gov/subjects/geology/americas-geoheritage.htm
- NPS Geoheritage Sites - Examples on Public Lands, Natural Landmarks, Heritage Areas, and The National Register of Historic Places: https://www.nps.gov/subjects/geology/geoheritage-sites-listing-element.htm
- UNESCO Global Geoparks: https://en.unesco.org/global-geoparks
- U.S. Geoheritage & Geoparks Advisory Group: https://www.americasgeoheritage.com/

Geologic Maps

- The American Geosciences Institute provides information about geologic maps and their uses: http://www.americangeosciences.org/environment/publications/mapping
- *General Standards for Geologic Maps* (Evans 2016)
- National Geologic Map Database: https://ngmdb.usgs.gov/ngmdb/ngmdb_home.html

Geological Surveys and Societies

- California Geological Survey: https://www.conservation.ca.gov/cgs
- US Geological Survey: http://www.usgs.gov/
- Geological Society of America: http://www.geosociety.org/
- American Geophysical Union: http://sites.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: http://www.stategeologists.org/

Landslides and Slope Movements

- The NPS Geologic Resources Division employs three rockfall management strategies: (1) an Unstable Slope Management Program (USMP) for transportation corridor risk reduction, (2) quantitative risk estimation for specific rockfall hazards, and (3) monitoring of potential rockfall areas. Park managers can contact the Geologic Resources Division to discuss these options and determine if submitting a technical assistance request is appropriate.
- *Geological Monitoring* (Young and Norby 2009) chapter about slope movements (Wieczorek and Snyder 2009): http://go.nps.gov/geomonitoring
- *The Landslide Handbook—A Guide to Understanding Landslides* (Highland and Bobrowsky 2008): http://pubs.usgs.gov/circ/1325/

NPS Geology

- NPS Geologic Resources Division (Lakewood, Colorado) *Energy and Minerals*; *Active Processes and Hazards*; *Geologic Heritage*: http://go.nps.gov/geology
- NPS Geodiversity Atlas: https://www.nps.gov/articles/geodiversity-atlas-map.htm
- NPS Geologic Resources Inventory: http://go.nps.gov/gri
- NPS Geoscience Concepts website: https://www.nps.gov/subjects/geology/geology-concepts.htm

NPS Reference Tools

- NPS Technical Information Center (TIC; repository for technical documents and means to receive interlibrary loans): https://www.nps.gov/orgs/1804/dsctic.htm
- GeoRef. The GRI team collaborates with TIC to maintain an NPS subscription to GeoRef (the premier online geologic citation database) via the Denver Service Center Library interagency agreement with the Library of Congress. Multiple portals are available for NPS staff to access these records. Park staff can contact the GRI team or GRD for access.
- NPS Integrated Resource Management Applications (IRMA) portal: https://irma.nps.gov/. *Note*: The GRI team uploads scoping summaries, maps, and reports to IRMA. Enter "GRI" as the search text and select a park from the unit list.
- The NPS Social Sciences Program coordinates visitation statistics reporting for NPS units. Data and reports are available to view and download at the IRMA/STATS webpage (https://irma.nps.gov/STATS/).

Pinnacles National Park Area Geology Publications and Guidebooks

- *Roadside geology of Northern and Central California* (Alt and Hyndman 2000)
- *Finding fault in California: an earthquake tourist's guide* (Hough 2004)
- *Geology of Point Reyes Peninsula and implications for San Gregorio Fault history* (Clark et al. 1984)
- *A land in motion: California's San Andreas Fault* (Collier 1999)
- *Geology: substrate and soils* (Evens 1993)
- *Geologic trips: San Francisco and the Bay Area* (Konigsmark 1998)
- *Where's the San Andreas Fault? A guidebook to tracing the fault on public lands in the San Francisco Bay region* (Stoffer 2006)
- *The San Andreas Fault system, California* (Wallace 1990)

Relevancy, Diversity, and Inclusion

- NPS Office of Relevancy, Diversity and Inclusion: https://www.nps.gov/orgs/1244/index.htm
- Changing the narrative in science & conservation: an interview with Sergio Avila (Sierra Club, Outdoor Program coordinator). Science Moab radio show/podcast: https://sciencemoab.org/changing-the-narrative/

US Geological Survey Reference Tools

- Geologic Names Lexicon (Geolex; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/search
- Geographic Names Information System (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/
- USGS Store (find maps by location or by purpose): http://store.usgs.gov
- National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/ngmdb/ngmdb_home.html
- Tapestry of Time and Terrain (descriptions of physiographic regions; Vigil et al. 2000): http://pubs.usgs.gov/imap/i2720/
- USGS Publications Warehouse : http://pubs.er.usgs.gov

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These references are cited in this report. Contact the Geologic Resources Division for assistance in obtaining them.

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NPS 114/186433, October 2022

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