National Park Service
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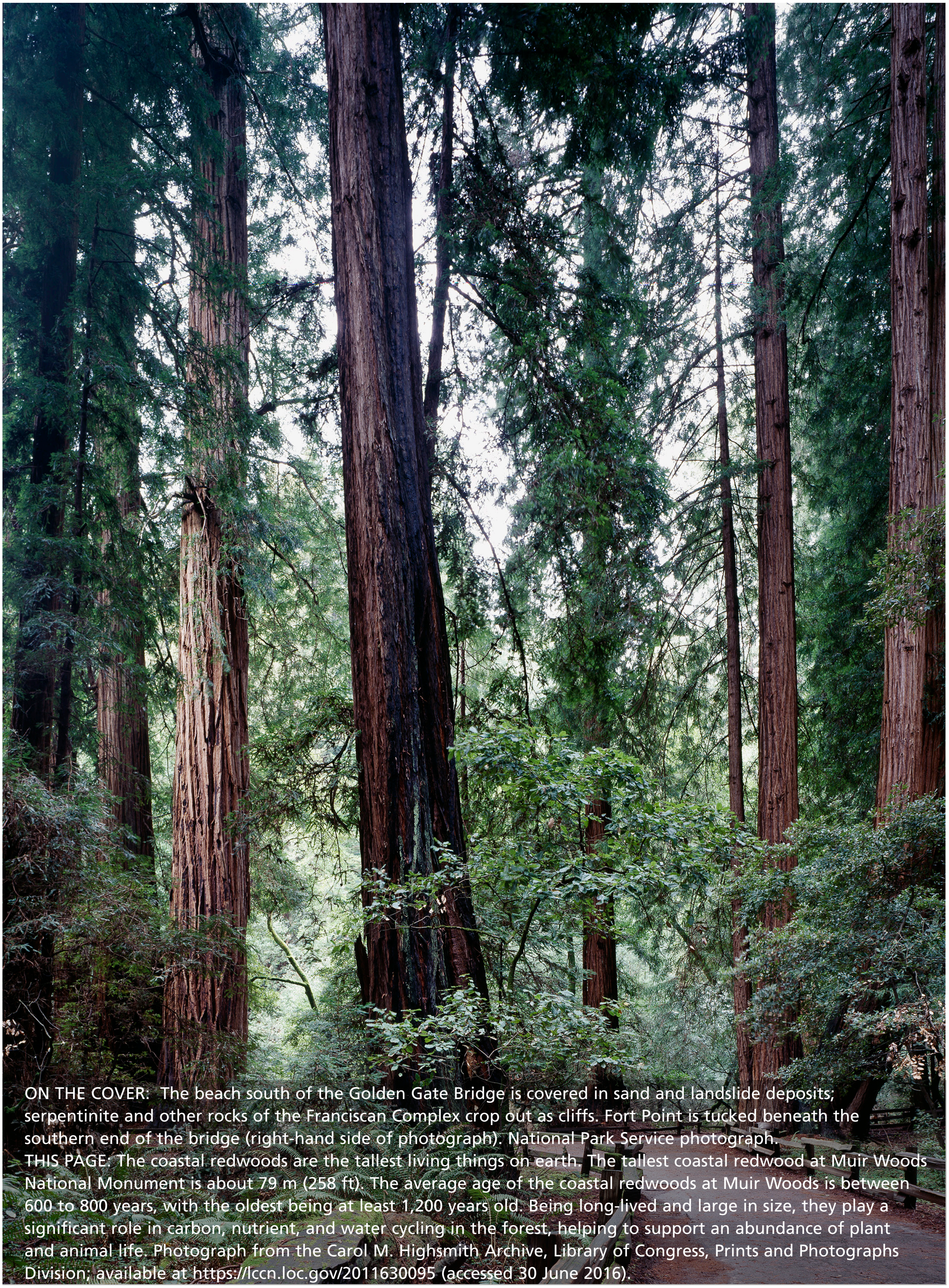
Natural Resource Stewardship and Science

Golden Gate National Recreation Area, including Fort Point National Historic Site and Muir Woods National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2016/1266



ON THE COVER: The beach south of the Golden Gate Bridge is covered in sand and landslide deposits; serpentinite and other rocks of the Franciscan Complex crop out as cliffs. Fort Point is tucked beneath the southern end of the bridge (right-hand side of photograph). National Park Service photograph.
THIS PAGE: The coastal redwoods are the tallest living things on earth. The tallest coastal redwood at Muir Woods National Monument is about 79 m (258 ft). The average age of the coastal redwoods at Muir Woods is between 600 to 800 years, with the oldest being at least 1,200 years old. Being long-lived and large in size, they play a significant role in carbon, nutrient, and water cycling in the forest, helping to support an abundance of plant and animal life. Photograph from the Carol M. Highsmith Archive, Library of Congress, Prints and Photographs Division; available at https://lccn.loc.gov/2011630095 (accessed 30 June 2016).

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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.

The Natural Resource Report Series is used to disseminate comprehensive information and analysis about natural resources and related topics concerning lands managed by the National Park Service. The series supports the advancement of science, informed decision-making, and the achievement of the National Park Service mission. The series also provides a forum for presenting more lengthy results that may not be accepted by publications with page limitations.

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.

This report is available from the Geologic Resources Inventory website (http://go.nps.gov/gripubs), and the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm/). To receive this report in a format optimized for screen readers, please email irma@nps.gov.

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Executive Summary

This Geologic Resources Inventory (GRI) report synthesizes discussions regarding Golden Gate National Recreation Area (California), including Fort Point National Historic Site and Muir Woods National Monument, from a scoping meeting on 26–28 September 2007 and a conference call on 6 May 2014. These discussions were convened by the National Park Service (NPS) Geologic Resources Division to identify geologic resources and geologic resource management issues and needs, and determine the status of geologic mapping. The report is a companion document to the previously completed GRI GIS data.

This GRI report was written for resource managers to support science-informed decision making in light of laws, regulations, and policies that specifically apply to NPS minerals and geologic resources (see Appendix B). It may also be useful for interpretation. The report was prepared using available geologic information, and the NPS Geologic Resources Division conducted no new fieldwork in association with its preparation. Chapters of the report discuss distinctive geologic features and processes within Golden Gate National Recreation Area, including Fort Point National Historic Site and Muir Woods National Monument; highlight geologic issues facing resource managers; describe the geologic history leading to the present-day landscape; and provide information about the GRI GIS data. Posters (in pocket) illustrate these data. The Map Unit Properties Table (in pocket) summarizes report content for each geologic map unit within the authorized boundary of the recreation area.

Golden Gate National Recreation Area was established in 1972, largely from former military lands, "to offer national park experiences to a large and diverse urban population while preserving and interpreting the outstanding natural, historic, scenic, and recreational values of the park lands." The recreation area preserves natural features such as coastal beaches and shorelines and the adjacent hills and mountains in the San Francisco Bay Area.

The recreation area is spread across San Mateo, San Francisco, and Marin counties. Since its establishment, it has expanded several times and now covers more than 32,000 ha (80,000 ac). The authorized boundary for the recreation area far exceeds the lands actually managed by the National Park Service. Areas within the boundary that are managed by other public agencies include the San Francisco Watershed in San Mateo County, Angel Island State Park, and lands surrounding Mount Tamalpais State Park north of the Marin Headlands. Within the area managed by the National Park Service are two other national park units—Fort Point National Historic Site and Muir Woods National Monument. Reference to "the park" throughout this report refers to the National Park Service–managed areas of Golden Gate National Recreation Area, Fort Point National Historic Site, and Muir Woods National Monument. The boundary of Golden Gate National Recreation Area also encompasses San Francisco Maritime National Historical Park, but that park is not part of the San Francisco Bay Area Inventory and Monitoring Network and is, therefore, not included in this inventory report.

Fort Point is a Civil War–era brick and mortar masonry structure that has stood guard at the narrows of the "Golden Gate" since its completion in 1861 at the height of the California Gold Rush. While Fort Point never saw battle, it is still significant with respect to military history; the fort played a role in the harbor defenses of San Francisco in both the Civil War and World War II. The fort would have been demolished during the construction of the Golden Gate Bridge in the early 1930s, but apparently Joseph Strauss, the bridge's chief engineer, decided to save the fort because of its exquisite masonry work. The fort is also significant for its association with maritime history; three lighthouses have stood at Fort Point. Fort Point officially became a national historic site and National Register property in 1970. The fort and surrounding 12 ha (29 ac) comprise Fort Point National Historic Site.

Muir Woods is the only old-growth coastal redwood forest in the Bay Area and one of the last on the planet. It was the first of the three NPS units discussed in this report to be established. In 1905 William and Elizabeth Kent purchased the land that would become the monument and donated it to the federal government to create what John Muir described as "the best treelover's monument that could possibly be found in all the forests of the world." In 1908, Muir Woods was declared a national monument to protect an "extensive growth of redwood trees" and lands of "extraordinary scientific interest and importance because of the primeval character of the forest…and the character, age, and size of the trees." The average age of the coastal redwoods at Muir Woods is between 600 and 800 years, with the oldest being at least 1,200 years old. The monument's establishment was due to a remarkably strong local conservation movement that continued for decades and led to the establishment of many public lands in the Marin Headlands, including Golden Gate National Recreation Area.

The geologic setting of the park and the San Francisco Bay Area is active, complex, and well-studied; key geologic features are present within the park. Geologic features and processes identified in the park include the following:

- **Rocks of the Franciscan Complex**. Most of the basement rocks in the park belong to the Franciscan Complex. These rocks were originally deposited in a marine environment in a sequence beginning with basalt and greenstone, followed by chert and limestone, and finally graywacke sandstone and shale. Subsequently, the rocks were metamorphosed in a subduction zone and accreted to the North American continent. Serpentinite (hydrothermally altered ancient oceanic crust) and other hydrothermal and metamorphic rocks also occur in the Franciscan Complex.
- **Franciscan Terranes**. The Franciscan Complex is divided into terranes that represent distinct episodes of accretion onto the North American continent. The terranes consist of blocks of Franciscan rocks in which the original depositional sequence is sometimes still visible.
- **Franciscan Mélange**. Mélange are zones of "crushed up" and "mangled" Franciscan rocks that separate the different terranes. Because mélange is so sheared, it is easily eroded into rounded hills throughout the park. Franciscan mélange is often referred to as the "Central terrane."
- **Rocks of the Salinian Complex**. The Salinian complex is composed primarily of the igneous rock granite. It originated from the same massive batholith that formed the core of the Peninsular Ranges and Sierra Nevada. A sliver of this complex was carried north along the San Andreas Fault, and today it forms Montara Mountain and much of the basement rocks in Point Reyes National Seashore.
- **Cenozoic Rocks and Deposits**. Sedimentary rocks were deposited in the park, largely by surficial processes, during the last 66 million years. During this time, tectonism in the San Francisco Bay Area evolved from a subduction to a transform regime; the rocks deposited during this time reflect this complex transition. Tension, compression, and localized faulting associated with the development of the San Andreas Fault broke the pre-Cenozoic bedrock into blocks which created basins and uplifts. Cenozoic rocks are primarily conglomerate or sandstone and their depositional settings range from marine to coastal to nonmarine.
- **Folds**. The only folds mapped within the park's boundary (and included in the GRI GIS data) are near Point San Pedro and Seal Cove. Smaller folds are common at outcrop scale within the park and include the tight "chevron" folds of the ribbon chert along Conzelman Road.
- **Faults and the San Andreas Fault System**. Nearly 390 km (240 mi) of faults are mapped in the park. The San Andreas Fault is the most well-known but not the only fault in the San Francisco Bay Area. In actuality, the San Andreas Fault is not a single fault but a system of many faults that accommodate transform plate motion between the Pacific and North American tectonic plates. Thrust faults, which separate terranes and zones of mélange, are also a common feature in the park. Thrust faults are responsible for bringing Franciscan rocks toward the surface; erosion is exposing these rocks today.
- **Earthquakes**. Earthquakes are ubiquitous in the San Francisco Bay Area. Most of the major earthquakes in California are caused by movements along faults of the San Andreas Fault system. Many of the faults in this system are seismically connected, meaning that an earthquake along one could generate movement on another.
- **Geothermal Systems and Hydrothermal Features**. The park is not known for geothermal resources or hydrothermal features and is not included on the list of 16 parks that are designated under the Geothermal Steam Act of 1970, as amended in 1988. However, one hot spring occurs in the park. It is along the coast at the north end of Steep Ravine Beach.

- **Paleontological Resources**. The park contains considerable paleontological resources from the remains of Cenozoic Era mammals to Mesozoic Era marine invertebrates, and the potential for continued discovery is considerable. A paleontological resource inventory for the park was completed in 2015.
- **Landslide Deposits and Slope Movements**. Four types of slope movement are common in the San Francisco Bay Area—rockfall, slumps, debris slides, and earth/debris flows—though others can and do occur. Slope movements occur primarily in weak rocks, such as mélange, serpentinite, and unconsolidated Quaternary deposits. Slope movements also occur on steep slopes, such as those along the coast. Heavy rain, earthquakes, and undercutting of steep slopes have triggered slope movements in the park.
- **Alluvium and Fluvial Processes**. Dynamic fluvial systems, including rivers, streams, and creeks, have deposited alluvium in the park throughout the last 2.6 million years (Quaternary Period). Recent alluvium is found primarily in active drainage channels and valleys. Older alluvial deposits give insight to the history of development of the modern San Francisco watershed.
- **Coastal Features and Processes**. The coastline of the park features cliffs and bluffs, beaches and dunes, and calm bays and estuaries. Distinctive processes operate in each environment, and each responds differently to the impacts of climate change such as changes in sea level and rates of erosion. Slope movements are common on coastal cliffs. Beaches and dunes change size and shape seasonally in response to wave energy and storms.
- **Sea Caves**. Sea caves are a common feature along the coast of California. Sea caves form where waves and the sediments they carry exploit and enlarge weak zones (joints, fractures, and fissures) in otherwise erosion-resistant, cliff-forming rock. Sea caves are more common in the harder and older rocks of the Franciscan Complex than in the softer and younger Cenozoic-age sedimentary rocks. The exact number of caves in the park is unknown, but the number is likely at least 100 and potentially more than 500. Due to accessibility challenges, a formal cave inventory has not yet been completed.

Potential geologic resource-related management issues identified during the GRI scoping meeting and follow-up conference call include the following:

- **Earthquake Probability, Hazards, and Risks**. Probabilities for a strong (magnitude 6.7) earthquake in the next 30 years are between 0.30 and 0.50 (30% to 50% "chance") for the park. For the entire San Francisco Bay region, that probability increases to 0.72 (72% "chance") for a magnitude 6.7 earthquake somewhere in the region between 2014 and 2043. All of the park's area is at the highest levels of relative risk for earthquake shaking intensity and damage. Both fault "creep" and surface rupture offset and deform surface structures creating a safety hazard and causing costly damage. The primary strategy to reduce risk associated with creep and surface rupture is to avoid building infrastructure across mapped faults. Liquefaction hazard is acute around the margin of San Francisco Bay, where significant damage has taken place during large earthquakes. Earthquake damage is most severe when shaking is compounded by ground failures such as landslides or liquefaction. Earthquakes under the ocean may generate large waves called tsunamis. Earthquakes hundreds or thousands of kilometers away could produce tsunamis that may affect Golden Gate National Recreation Area and Fort Point National Historic Site.
- **Slope Movement Hazards and Risks**. Slope movements in the park are a natural process but also constitute a common type of geologic hazard. In the park, areas of steep slopes, such as coastal cliffs, and weak rocks, such as mélange, serpentinite, and landslide deposits, are the most susceptible to slope movements, particularly during times of intense rainfall and earthquakes. Climate change may be impacting the rate and intensity of landslides in the park. Detailed geologic maps are vital to assessing slope movement hazards and risks.
- **Flooding**. An understanding of flood potential is needed in making land-use decisions. A particular concern is flood potential on alluvial fans because these landforms shift. The California Geological Survey may be able to produce a map of relative flood potential on alluvial fans in the park.
- **Sea Level Rise**. Climate change-related sea level rise has the potential to impact many of the facilities and natural features and processes in the park.

Predicting how sea level change will affect park resources is complex, but the National Park Service has a variety of resources to assist park managers with the challenge of factoring sea level rise into park management plans, project plans, and coastal adaptation strategies.

- **Coastal Resource Management and Planning**. The National Park Service has developed a variety of data sets and guidance for managing coastal resources and planning for the impacts of climate change. The Geologic Resources Division may be able to provide coastal resource management and planning assistance in the form of site specific investigations.
- **Coastal Erosion and Sediment Dynamics**. Climate change, modifications to sediment input, and coastal engineering projects have resulted in intensified coastal erosion and altered sediment dynamics at the park. Human activities have dramatically reduced the amount of sediment in the San Francisco Bay coastal system which in turn affects offshore features that play an important role in dissipating wave energy and limiting coastal erosion. Sea level rise and more frequent and intense winter storms associated with climate change, as well as El Niño and associated changes in sea level and wave direction, will probably further exacerbate coastal erosion.
- **Marine Features and Offshore Mapping**. Much is still unknown about the marine environment of the park. Recently completed offshore maps will aid in identifying and monitoring important marine features in the park.
- **Sea Cave Documentation and Management**. The Federal Cave Resources Protection Act of 1988 requires the identification of "significant caves" in National Park Service areas, the regulation or restriction of use as needed to protect cave resources, and inclusion of significant caves in land management planning. Planning for a sea cave inventory is underway. A park-specific cave management plan has not yet been completed.
- **Paleontological Resource Inventory, Monitoring, and Protection**. All paleontological resources are subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act. Threats to paleontological resources in the park include unauthorized (non-permitted) collecting, vandalism, and erosion. The paleontological resource inventory and other reports for the park provide a list of suggested ways to better protect, document, and understand fossil resources, and to share and expand paleontological knowledge.
- **Monitoring Aeolian Resources**. Dunes protect the shoreline from the impacts of waves and storms and provide habitat for a variety of plants and animals. Dunes once covered the majority of San Francisco but have been largely removed by development. Monitoring the dune fields that remain could assist park managers in determining dune growth trends and which areas require protection.
- **Geothermal Resource Protection**. The only known hot spring in the park is near Steep Ravine Beach; it is not in an NPS-managed area. Based on limited documentation, it does not appear to require resource protection.
- **Coastal Serpentine Scrub Preservation**. Resource managers are very interested in the location of serpentinite outcrops and serpentine soils because rare and endemic vegetation is associated with these geologic resources. The GRI GIS data that accompany this report, soil resource inventories, and a vegetation inventory map are available to assist with locating existing and predicting yet-to-be-discovered areas of coastal serpentine scrub.
- **Disturbed Land Restoration**. Many potential disturbed land restoration projects exist within the park as a result of past military and agricultural land uses and urban development. Much work has already been done in the Presidio and Crissy Field, and a restoration project at the Redwood Creek area is currently underway. Due to budget and staffing limitations, many potential disturbed land restoration projects have not been initiated.
- **Naturally Occurring Hazardous Materials**. Asbestos occurs naturally in California in serpentinite and partially serpentinized ultramafic rocks. Mercury occurs naturally in the mineral cinnabar, which is associated with silica carbonate rocks found with serpentinites. Both mercury and asbestos may be hazardous to human health and the environment.
- **Groundwater Contamination**. Contamination of groundwater by introduction of pollution from the surface is a major issue in the San Francisco Bay Area. Soil and groundwater contamination in the parks is largely related to past military land

uses. Geology influences contamination in that pollutants tend to follow high-porosity Holocene stream channel and levee deposits. Aging septic systems impact surface water quality. Park managers are referred to the NPS Water Resources Division for technical assistance with groundwater-related issues.

- **Abandoned Mineral Lands**. According to the NPS servicewide abandoned mineral lands database, Golden Gate National Recreation Area contains 23 abandoned mineral land features at 5 sites. Some features are culturally significant, such as the limestone quarry near Mori Point that was mined by the Spanish in the 1700s to supply whitewash for Presidio buildings. Abandoned mineral lands present a variety of resource management issues such as visitor and staff safety and environmental quality of air, water, and soil. These features can also provide habitat for bats and other animals.
- **External Energy and Mineral Development**. Aggregate mining occurs today in designated lease areas within and adjacent to the park. Continued communication among park managers, the San Francisco Bay Conservation and Development Commission, and other agencies is needed to ensure that National Park System resources and values are not adversely impacted by external mineral exploration and development.
- **Renewable Energy Development**. Park managers are concerned about the impacts of proposed tidal, wind, and wave energy projects. The NPS Pacific West Regional Office has been working with park staff to review and comment on alternative energy proposals.

Products and Acknowledgments

The Geologic Resources Inventory is one of 12 inventories funded by the NPS Inventory and Monitoring Program. The Geologic Resources Division (GRD) of the Natural Resource Stewardship and Science Directorate administers the Geologic Resources Inventory. The GRD partners with institutions such as Colorado State University, the US Geological Survey, state geological surveys, local museums, and universities to develop GRI products.

GRI Products

The objective of the Geologic Resources Inventory is to provide 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. To realize this objective, the GRI team undertakes three tasks for each natural resource park: (1) conduct a scoping meeting and provide a summary document, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report (this document). These products are designed and written for nongeoscientists.

Scoping meetings bring together park staff and geologic experts to review and assess available geologic maps, develop a geologic mapping plan, and discuss geologic features, processes, and resource management issues that should be addressed in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to digital geologic map data in accordance with the GRI data model. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the GRI report.

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

Additional information regarding the GRI, including contact information, is available at http://go.nps.gov/gri. The current status and projected completion dates of products are available at http://go.nps.gov/gri_status.

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The GRI team thanks **Will Elder** (Golden Gate National Recreation Area) for providing invaluable comments, suggestions, and publications which vastly improved the quality and utility of this report; **Kenneth** and **Gabrielle Adelman** of the California Coastal Records Project for permitting the use of their collection of coastal photographs; **Brian Ullensvang** (Golden Gate National Recreation Area) for his review of the section on naturally occurring hazardous materials; **Eric Bilderback** (NPS Geologic Resources Division) for his review of the slope movement sections; **Courtney Schupp** (NPS Geologic Resources Division) for her review of the coastal features, processes, and issues sections; **Dale Pate** (NPS Geologic Resources Division) for his review of the sea cave sections; and **Trista Thornberry-Ehrlich** (Colorado State University) for providing graphic design expertise.

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Geologic Setting and Significance

This chapter describes the regional geologic setting of Golden Gate National Recreation Area, including Fort Point National Historic Site and Muir Woods National Monument, and summarizes connections among geologic resources, other park resources, and park stories.

Park Setting

Nowhere on Earth do geology and people intersect as they do at Golden Gate National Recreation Area. Both opportunity and risk abound in this park, one of the most-visited in the National Park System. Here, earthquakes, landslides, stunning landforms, dramatic coastline, and a magnificent variety of rocks are the status quo for as many as 15 million visitors annually.

Golden Gate National Recreation Area was established on 27 October 1972. It is situated in and around the second-most densely populated major city in the United States—San Francisco (US Census Bureau 2013)—and consists of a collection of NPS–administered areas, including two previously established NPS units—Muir Woods National Monument and Fort Point National Historic Site—that are now administered as part of the national recreation area (fig. 1). The authorized boundary for the recreation area far exceeds the lands actually managed by the National Park Service (see posters, in pocket). Golden Gate National Recreation Area, Muir Woods National Monument (established in 1908), and Fort Point National Historic Site (established in 1970) are parks within the San Francisco Bay Area Inventory and Monitoring (I&M) Network, and as such are included in this Geologic Resources Inventory that is conducted as part of the I&M Program. This report collectively refers to these three NPS units as "the park." San Francisco Maritime National Historical Park is not part of the I&M Program and is not specifically addressed in this report.

The park is as diverse as it is expansive, extending from southern San Mateo County to northern Marin County, including several areas of San Francisco. The park is west of San Francisco and San Pablo bays, and both north (Marin County) and south (San Francisco and San Mateo counties) of the Golden Gate strait. It encompasses natural and cultural resources such as iconic coastal scenery (Marin Headlands), a famous fault (San Andreas), an infamous prison (Alcatraz Island), massive trees (Muir Woods), US military fortifications (Fort Point), and the site of the initial Spanish fortification in San Francisco (the Presidio).

The park's landscape is varied, consisting of nearly flat marine terraces and alluvial deposits, steep canyons, rolling hills, rugged coastal bluffs, as well as islands, peninsulas, and bays. Elevations range from sea level to 784 m (2,572 ft) at Mount Tamalpais. A great variety of rocks exist in the park because of the tectonic setting and geologic processes, operating both now and in the past. For millions of years, plate tectonics, as well as surface and coastal processes, have been creating, transporting, and altering these rocks. Vegetation is similarly diverse and includes endemic plant communities such as coastal serpentine scrub.

The park's topography is characteristic of the California Coast Ranges which is part of the Pacific Border physiographic province, one of four provinces represented in the state of California. The mountains span more than 600 km (400 mi) along the coast and consist of a series of parallel ranges and valleys oriented northwest to southeast. The largest of the valleys is partly filled by San Francisco and San Pablo bays (fig. 2). The Coast Ranges landscape attests to more than 200 million years of active—and ongoing—geologic processes driven by plate tectonics, the sculpting power of the Pacific Ocean, abundant precipitation, and slope movements. Human modifications have also transformed the landscape.

Plate Tectonic Setting

Many of the geologic processes that shaped the landscape of the Coast Ranges and the park are related to plate tectonics. The theory of plate tectonics revolutionized the science of geology in the 1960s by providing global scale mechanisms for the formation and changing size, shape, orientation, and location of Earth's most massive features—mountain ranges, ocean basins, and even entire continents. Plate tectonics asserts that convection within the Earth, in the hot and "soft" rocks of the mantle, drives movement on the Earth's surface, called the "crust," which is broken into rigid slabs referred to as tectonic plates. The plates may converge, which consumes crust, diverge, which

Figure 1. Map of Golden Gate National Recreation Area. The area managed as Golden Gate National Recreation Area is spread throughout the San Francisco Bay Area. Fort Point National Historic Site and Muir Woods National Monument are managed by Golden Gate National Recreation Area staff. The authorized boundary, also called the "legislative boundary", for the recreation area far exceeds the lands actually managed by the National Park Service (see posters, in pocket). National Park Service map.

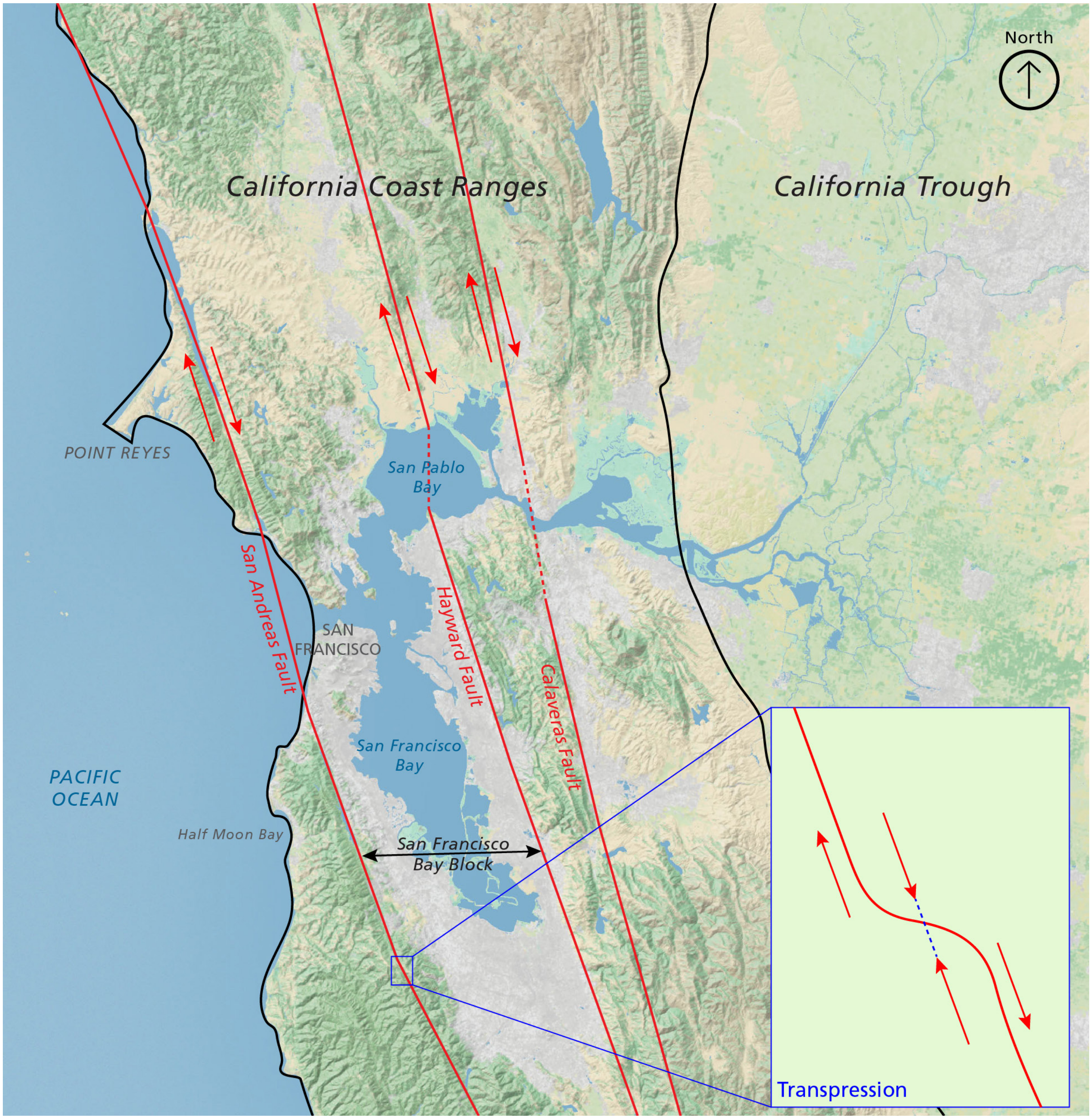


Figure 2. Simplified physiographic and fault map of the San Francisco Bay Area. The California Coast Ranges are a series of parallel mountain ranges and valleys, the largest of which runs through San Francisco and San Pablo bays. Black lines show the boundaries between physiographic sections. The California Trough physiographic section is to the east of the California Coast Ranges. Red lines show the approximate location of a selection of faults in the San Andreas Fault system and red arrows show the relative transform movement along each fault. Each fault block moves northwest relative to the block to its east. The faults are not perfectly straight as they appear on this simplified graphic. Locally, where faults bend to the left, compression takes place with the transform movement (transpression) as shown by the dashed line on the inset graphic. Transpression causes crustal shortening and results in a hilly landscape. Where faults bend to the right, extension takes place, such as at San Pablo Bay. Shaded relief map by Tom Patterson (National Park Service). Annotations by the author.

allows new crust to form, or slide past each other at a transform boundary, which neither creates nor destroys crust. Today, the park is bisected by a transform boundary (the San Andreas Fault system) which is relocating rocks that were originally associated with ancient convergent and divergent boundaries.

Modern Transform Boundary along the San Andreas Fault

The park is located along the modern transform boundary between the North American plate, which is moving to the southeast, and the Pacific plate, which moving to the northwest. The plates are currently sliding (or rather grinding) past each other at a rate of approximately 2.5–5 cm (1–2 in) per year (Sloan 2006; Field et al. 2015). The plate boundary is often considered to be the San Andreas Fault, though this is a simplified view because plate movement is accommodated by a system of many faults. Most of the park's land is on the North American plate—east of the San Andreas Fault—and part of the "San Francisco Bay fault block" which is surrounded by other faults and blocks of the San Andreas Fault system (fig. 2). By contrast, Point Reyes National Seashore is on the Pacific plate—west of the San Andreas Fault. Transform movement initiated in Southern California about 28 million years ago and began extending through the San Francisco Bay Area only about 10 million years ago (see "Geologic History" chapter; Atwater 1970, 1989; Page and Wahrhaftig 1989).

In addition to transform movement, compression is a component of the motion between the Pacific and North American plates. Compression began at least 3.5 million years ago and possibly even several million years earlier (Sloan 2006). Compression causes shortening of the crust. Locally, the rate of shortening has been approximately 10% the rate of slip over the past 6 million years (Sarna-Wojcicki et al. 1986). This combination of transform movement and compression is called transpression. Transpression occurs mainly at left bends in transform faults (fig. 2 inset).

The compressive force is causing the land on both sides of the fault to fold like wrinkles in a blanket; thrust and blind thrust faults also develop at these bends (Will Elder, Golden Gate National Recreation Area, park ranger, written communication, 30 October 2015). Much of the hilly landscape characteristic of the area was formed only in the last few million years as a result of this squeezing together of the two plates. Measurements of coastal uplift at various locations in the San Francisco Bay Area indicate that the land is presently rising at a rate of about 3–8 cm (1–3 in) a century (Sloan 2006). Major faults are commonly expressed at the surface as valleys because the sheared rocks of the fault zone are relatively soft and more susceptible to erosion (Wallace 1990).

Ancient Convergent Boundary

The rocks underlying the park were assembled under an ancient tectonic setting, a convergent plate boundary. Beginning about 160 million years ago (Jurassic Period), the Farallon plate—an ancient oceanic plate—converged with the western edge of the North American continental plate (fig. 3, see "Nevadan orogeny"). Because oceanic crust is denser than continental crust, the Farallon plate sank beneath the North American plate at what is termed a "subduction zone." This subduction zone spanned the entire western edge of North America (see "Geologic History" chapter).

Geologists refer to the section of the subduction zone that was off California during the Mesozoic Era as the "Franciscan subduction zone." Franciscan subduction occurred from about 160 million to 50 million years ago (Elder 2013). Today, remnants of the Franciscan subduction zone persist where convergence continues off the coast of northern California, Oregon, and Washington (Cascadia Subduction Zone), and southern Alaska (Aleutian Trench). Volcanoes of the Cascade Range and Aleutians mark the locations of these modern subduction zones.

Certain geologic settings, such as an oceanic trench, forearc basin, and volcanic arc typically develop in association with a subduction zone (fig. 4). The majority of the basement rocks in the park and surrounding area formed (or at least assembled) in these geologic settings associated with the Franciscan subduction zone. Geologists divide the basement rocks into four groups: (1) the Franciscan Complex—a mostly Cretaceous accretionary wedge which formed in a deep oceanic trench, (2) the Salinian complex—relocated Cretaceous granitic rock that formed in association with a volcanic arc, (3) the Coast Range ophiolite—a section of Jurassic ocean crust that became trapped in a developing forearc basin, and (4) the Great Valley sequence—a thick, mostly Cretaceous, sedimentary sequence that filled a forearc basin (fig. 5). This section summarizes

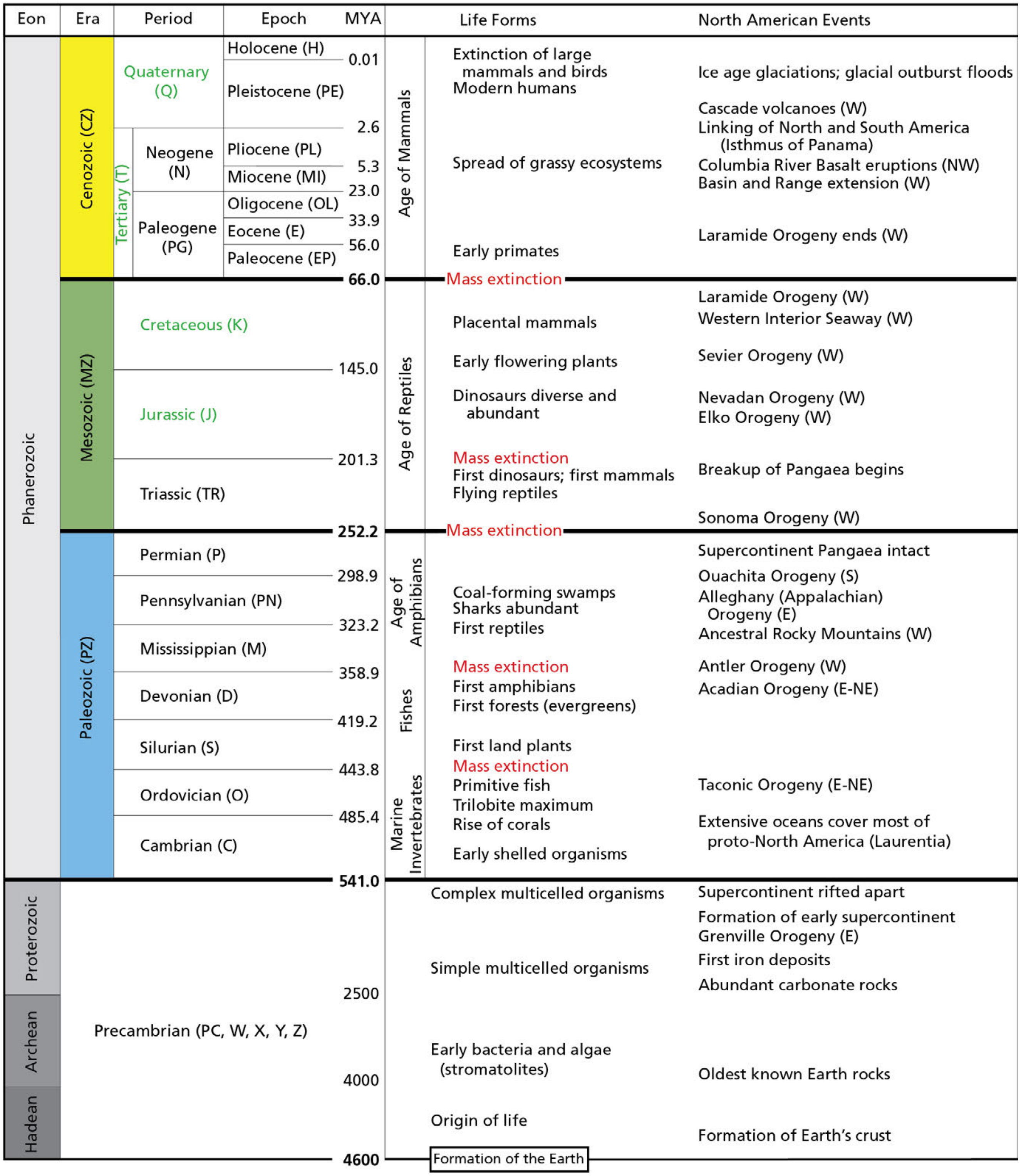


Figure 3. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. The Quaternary, Tertiary, Cretaceous, and Jurassic periods (green text) are represented by rocks or deposits in the GRI GIS data. Metamorphic rocks with less well defined ages are assigned to the Mesozoic and Paleozoic eras (MZPZ unit). Compass directions in parentheses indicate the regional locations of events. Boundary ages are millions of years ago (MYA). National Park Service graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale).

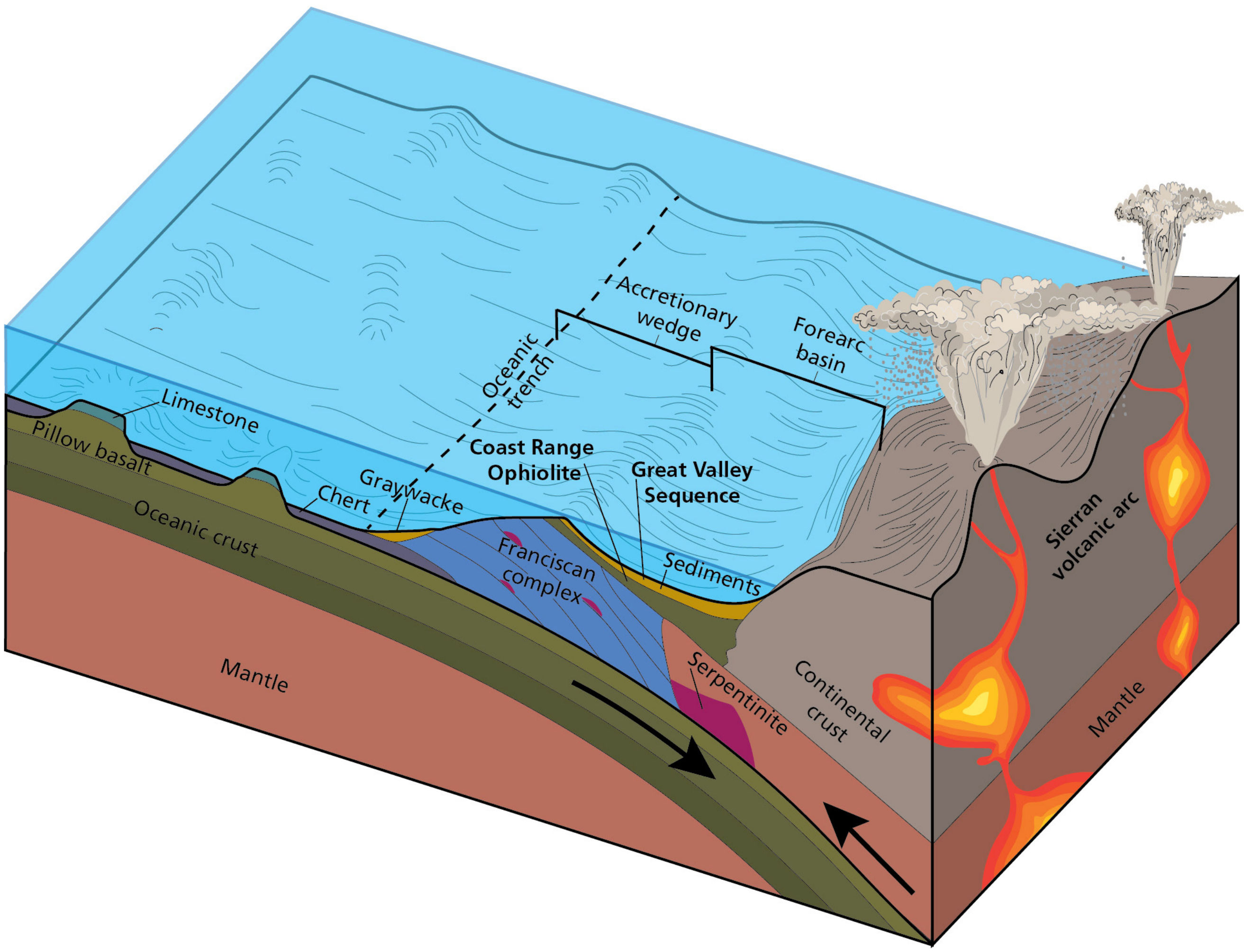


Figure 4. Illustration of the Franciscan subduction zone. The majority of the basement rocks in the park and surrounding area formed (or at least assembled) in geologic settings associated with the Franciscan subduction zone. The accretionary wedge, which would become the Franciscan Complex, formed when basalt, chert, and limestone traveled into the oceanic trench and were topped off by sediments eroded from the land (mainly graywacke sandstone). Salinian granite originated as part of a batholith in the Sierran arc. The Coast Range ophiolite was a piece of Jurassic ocean crust that became emplaced on the continent as the subduction zone was forming. The Great Valley sequence is a huge thickness of sedimentary rocks deposited on top of the Coast Range ophiolite within the forearc basin. Graphic by Trista Thornberry Ehrlich (Colorado State University), modified from Elder (2001, figure 3.3).

these groups and their associated geologic setting. See Elder (2013) for a more comprehensive discussion of Franciscan subduction.

Franciscan Complex

Rocks of the Franciscan Complex represent an accretionary wedge—an accumulation of sediment and rock—that collected in a deep oceanic trench. A trench marks the position at which a subducting plate flexes and descends beneath an overriding plate. The Franciscan accretionary wedge formed in this trench from sediments eroding off the land and from crustal rocks being scraped off of the subducting plate. The scraped-off rocks, in some cases, had traveled great distances on the Farallon plate to reach the subduction zone. The accretionary wedge materials became metamorphosed (deformed by heat and pressure) in the subduction zone and accreted (attached) to the overriding (non-subducting) continental plate. Today, the rocks of the Franciscan Complex underlie the majority of the park east of the San Andreas Fault.

Salinian Complex

The subduction of the Farallon plate triggered melting

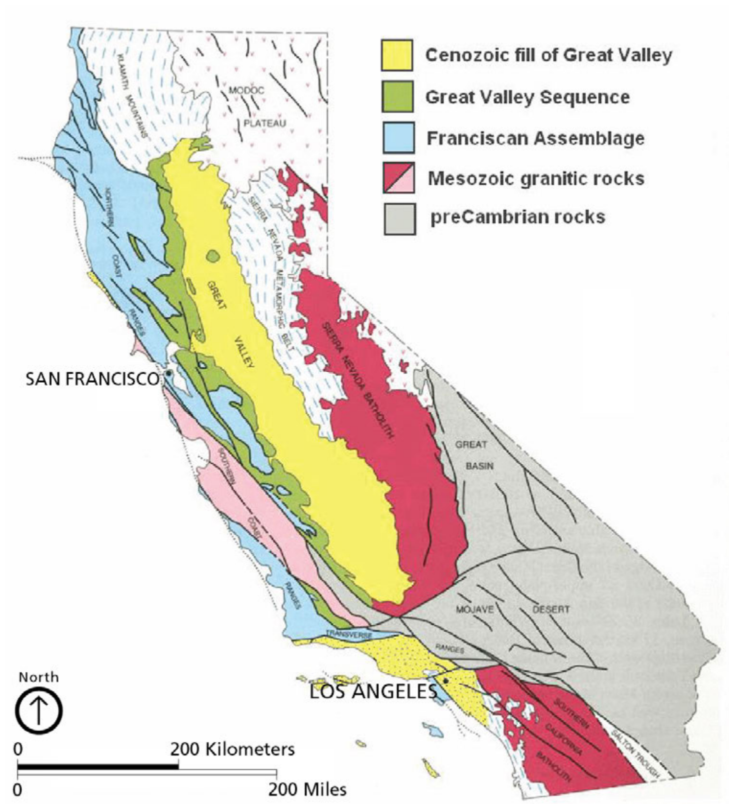


Figure 5. Map of California basement rocks. The basement rocks in the area of the park—the Great Valley sequence, the Franciscan assemblage (the Franciscan Complex), and Mesozoic granitic rocks (the Salinian complex)—formed in geologic settings associated with an ancient subduction zone (fig. 4). This figure shows the location of the rocks in California today. US Geological Survey graphic by Irwin (1990, fig. 3.3).

in the mantle, which ultimately produced an extensive volcanic arc system known as the Sierran arc (fig. 4). Where the subducting oceanic plate reached a depth of about 100 to 150 km (60 to 90 mi), heat resulted in partially melting of mantle material and the production of magma (molten rock). The newly formed magma, being less dense than continental rocks, rose toward the surface and produced a volcanic "arc"—a massive belt of batholiths (cooled magma chambers) and volcanoes—on the continental side of the plate boundary and parallel to the oceanic trench. Batholiths that fueled those volcanoes now comprise the iconic granitic landscapes of Yosemite National Park (see GRI report by Graham 2012). The Sierra Nevada batholith to the east of the park represents the eroded roots of a portion of the Sierran arc, which formed during Franciscan subduction (Dickinson et al. 1996).

The Cretaceous granitic rock of the Salinian complex is derived from the Sierran arc. However, it did not form in its current location; it originated in Southern California from the massive batholith that forms the core of the Peninsular Ranges. A sliver of this complex—the Salinian block—was later sliced off and carried north roughly 310 km (193 mi) by transform movement along the San Andreas Fault (Wentworth et al. 1998). Today, this portion is found on the west side of the San Andreas Fault at Montara Mountain and at Point Reyes National Seashore. It is overlain by Cenozoic sedimentary rocks primarily of marine origin. In the park, most of the area west of the San Andreas Fault, with the exception of the Pilarcitos fault block (see "San Andreas Fault System" section), is underlain by granitic rocks of the Salinian complex.

Coast Range Ophiolite

As plate convergence began, a low region called a forearc basin formed between the oceanic trench and the volcanic arc (fig. 4). The Coast Range ophiolite is a section of Jurassic ocean crust (probably map units **Jsv** and **Jgb**) that became trapped in the forearc basin as the subduction zone was coming together but before the accretion of the Franciscan Complex. Ophiolite is the name given to a section of oceanic crust that has been uplifted and emplaced onto and/or within continental crust. The Coast Range ophiolite originally formed as seafloor between 165 million and 153 million years ago (Jurassic Period) (Hopson et al. 1981). It was originally defined in the Bay Area by Bailey et al. (1970). Its exact origin, however, is still a matter of debate; Dickinson et al. (1996) presented several hypotheses.

The Coast Range ophiolite is important to the geologic story of the park because it is likely the original source of all the serpentinite in the San Francisco Bay Area (map units **KJfsu** and **KJspm**; see "Serpentinite" section). Ophiolite consists mainly of the rock peridotite, which may be metamorphosed into the rock serpentinite in subduction zones. The serpentinite was likely then "interleaved" (pushed between other rocks) along faults when the younger Franciscan Complex rocks were accreted (Blake et al. 2000). Alternatively, Coleman (2000) hypothesized that serpentinite may have been scraped directly off the subducting plate.

Great Valley Sequence

Around the same time that the Franciscan accretionary wedge was forming, underwater landslides in the forearc basin deposited the Great Valley sequence—an enormous thickness (as much as 8–9 km [5–6 mi] in the Diablo Range) of deep-water shale, silt, sandstone, and conglomerate turbidite beds—on top of the Coast Range ophiolite (Dickinson 1970; Dickinson and Rich 1972; Bartow and Nilsen 1990; Elder 2013). The sedimentary material was volcanic-rich and probably eroded from the ancient Klamath Mountains and volcanoes of the Sierra Nevada. Great Valley sequence rocks are not mapped in the park and are not part of the GRI GIS data. The Great Valley sequence is east of the park in the eastern Diablo Range and northern San Joaquin Valley. The Franciscan Complex is likely deeply buried beneath all of the Great Valley rocks (Blake et al. 2000). It is a matter of debate, but some research suggests that Franciscan rocks were thrust eastward and under both the Coast Range ophiolite and Great Valley sequence (Blake et al. 1984; Wakabayashi 1992).

Surficial Processes

Deformed, fractured, and faulted rocks of the Franciscan Complex are particularly susceptible to "surficial processes" such as erosion (marine and fluvial) and slope movements. These processes are responsible for a number of resource management issues as described in that chapter of this report. Rocks along the many faults in the area can be "ground up" due to the tectonic stresses, making them weak and easily eroded into valleys (Sloan 2006). Along the San Andreas Fault north of the Golden Gate, the long, linear valley occupied by Tomales Bay, Olema Valley, and Bolinas Bay is a good example (fig. 2). To the south of the Golden Gate, the valley continues through the water-filled and dammed depressions of San Andreas Lake and Crystal Springs Reservoir (fig. 2).

The GRI GIS data include a wide variety of Cenozoic rocks and sediments (see table 3) which were produced by surface processes and include bay mud, beach sand, marine terraces, stream channel deposits, stream terraces, alluvial fans, dune sand, landslide deposits, slope and ravine debris, and colluvium. The data also includes a variety of human-engineered, artificial fill deposits. Cenozoic units are largely displaced and broken up by faults, but they still may provide insight into the development of the modern San Francisco Bay watershed. The "Geologic Features and Processes" chapter provides details about the deposits in the park that are a result of surficial processes.

Geologic Connections

According to the General Management Plan, "physical landforms" are a "key interpretive theme" at the park because "the park's underlying natural geologic systems and processes, and the resulting effects on people and the environment, link the park to the highly visible and significant geologic forces around the world; geologic resources are the fundamental resources and values associated with this theme" (National Park Service 2014, p.S-iii). Indeed, Konigsmark (1998, p. 3) noted that "no other major city in the world has a greater variety of unusual and rare rocks that are easily accessible for observation" than San Francisco.

The trail to Point Bonita Lighthouse is the location of what is likely the earliest detailed geologic map in the state, completed by F. Leslie Ransome in 1893. This land of cliffs, beaches, bays, and rolling hills is the result of a long and complex geologic history, the clues to which are hidden within the many geologic features and in the active processes still occurring in the park. Even the old-growth coastal redwood forest of Muir Woods is connected to the geologic history of the area because time and geologic processes produced a landscape and soil suitable for these immense and stunning trees (see inside front cover).

Ecosystem Connections

The park is part of the United Nations (UNESCO) designated Golden Gate Biosphere Reserve and a number of threatened and endangered species live in the Golden Gate ecosystems. The ecosystems in the park are inherently tied to the landscape and therefore the geologic features and processes. Soil creates a connection between geologic bedrock and modern ecosystems. NPS Soil Resources Inventories have been completed for all three NPS units that are the subject of this report (National Park Service 2005a, 2005b, 2013) and provide detailed soils information. A number of products associated with the NPS Vegetation Inventory are also available (National Park Service 2003).

Some plants are endemic to habitats within the park. Examples of endemic plants include the dune tansy (*Tanacetum camphoratum*) and Hickman's potentilla (*Potentilla hickmanii*). The dune tansy is found on developed dune sands (**Qbs**, **Qdsy**) along the cliffs near Sutro Baths (Golden Gate NRA 2015a). In the late 1800s, the dune tansy was prized as an herbal remedy for a variety of ailments (Golden Gate NRA 2015a). Hickman's potentilla is a federally and state listed endangered plant of the rose family endemic to coastal San Mateo and Monterey counties (US Fish and Wildlife Service 2009). It is documented from Rancho Corral de Tierra in the park (Golden Gate NRA 2015b). Its habitat is strongly associated with weathered Salinian granite (**Kgr**) that underlies the thin grassland topsoil (US Fish and Wildlife Service 2009).

The coastal serpentine scrub, which is globally rare, also supports endemic plants. The coastal serpentine scrub community, located primarily on gentle slopes in the Presidio, developed atop serpentinite (rocks rich in serpentine minerals; described in the "Geologic Features and Processes" chapter). Because serpentine soils are unusually high in heavy metals such as zinc, nickel, and chromium (typically toxic to plants) and unusually low in essential nutrients such as potassium and calcium, they are home to many specially adapted, rare and endangered plants (Kruckenberg 1984). Eight of the 12 rare plant species found at the Presidio grow on serpentinite, including the federally endangered Presidio clarkia (*Clarkia franciscana*) and Raven's manzanita (*Arctostaphylos hookerii* ssp. *ravenii*); the latter was at one time represented by a single plant (Elder 2001). Recently, park staff reported a single example of Franciscan manzanita found only on the Presidio serpentine soils (Will Elder, park ranger, Golden Gate National Recreation Area, written communication, 30 October 2015). The Presidio clarkia is only found within the Presidio and East Bay Hills (Presidio of San Francisco 2015a).

Human Development, Fort Point, and Other Historic Structures

The park's namesake, "Golden Gate," refers to the strait connecting San Francisco Bay to the Pacific Ocean. The bay, isolated islands, and rugged headlands created a valuable landscape that supported commerce and facilitated defense. For hundreds of years, humans modified the landscape and built structures to suit their needs. These modifications are so extensive that they are noted on the geologic map. Geologic map unit **Qar** is artificial fill, **Qafs** are "Native American shell mounds," **Qmf** is fill placed over marine and marsh deposits, and **Qf1** and **Qf2** are fill related to development.

Prior to urban development, the San Francisco Peninsula was covered by sand dunes (see "Dunes" section and "Geologic History" chapter; Schlocker et al. 1958). The largest remaining dune field is at Fort Funston. The rolling terrain and moderate slopes in the central part of the city are modifications of the original landforms following deposition of "tremendous quantities" of dune sand (Schlocker et al. 1958). Although the creation of land via artificial fill allowed for expansive development of the city, particularly its waterfront, the fill now is responsible for serious resource management issues, particularly slope movements and liquefaction during earthquakes (see "Geologic Resource Management Issues" chapter). Resource managers continue to balance preservation of the historic significance of the various structures with natural processes that are inherently detrimental to those structures.

The park contains more than 700 historic ("classified") structures. Many are known to have local building stones; much building stone was also imported. Fort Point is among the most iconic of these structures and is the only classic 19th-century American coastal fort constructed on the west coast and the last of this style to be constructed anywhere in the United States (fig. 6; Golden Gate NRA 2006).

The story of Fort Point, which includes its construction as well as its preservation, is closely tied to geologic features and processes. A geologic feature provides the platform upon which the fort is built, geologic resources compose the fort, and geologic processes affect its preservation. The Cantil Blanco ("White Cliff") bluff has long been a strategic location. Its history of military fortifications extends back to the Spanish army in the late 1700s. During the 1850s the US Army wanted to construct a large fort on the site. Military technology of the time, however, dictated that the lowest level of guns in the fort should be as close to the water as possible. Therefore, in 1853, US Army engineers began to level the bluff from its natural position approximately 30 m (100 ft) above sea level down to only about 5 m (15 ft) above sea level. It took a construction crew an entire year to clear away enough of the serpentine-rich bluff to create a sufficient platform for the fort.

The fort itself was constructed of granite and brick (figs. 6 and 7). Initially, engineers planned to construct the entire fort using granite but three years into the

Figure 6. Exterior and interior views of Fort Point. The fort is composed of 8 million locally made bricks. The fort was considered significant enough in the 1930s to save while building the Golden Gate Bridge. Top: photograph copyright © 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, http://www.Californiacoastline.org, taken 27 September 2013, used with permission. Bottom: National Park Service photograph by Douglas Atmore.

Figure 7. Photographs of granite at Fort Point. Local Salinian granite did not meet the US Army's standards for construction. Therefore, decorative granite was sourced from the Mormon Island Quarries near Folsom, California. Clockwise from top left: exterior window, stairway entry in the west bastion, granite spiral staircase and landing. National Park Service photographs by John A. Martini.

project switched to bricks because local granite from the Salinian complex at Monterey and Point Reyes peninsulas did not meet the Army's high standards. For the foundation, engineers eventually chose granite from China because it was less expensive to source material from China than transport granite cross country from the northeast (Golden Gate NRA 2006). Some Chinese granite also arrived in San Francisco "accidentally" as ballast on ships from Asia. Decorative granite was sourced from the Mormon Island Quarries near Folsom, California (Golden Gate NRA 2006). The three spiral staircases which lead to the top barbette tier are made of Folsom granite (fig. 7). Approximately 8 million bricks were produced in a brickyard on the hill south of the fort (Golden Gate NRA 2006). These bricks were also used at Alcatraz (Golden Gate NRA 2006). For a more detailed list of the features in the fort that were constructed from granite refer to the *Abbreviated Fort Point Historic Structure Report* (Golden Gate NRA 2006).

Despite its massive size, the fort's location close to sea level afforded little protection against often damaging natural coastal processes such as wind and water erosion. Engineers immediately recognized this vulnerability and first relocated rock removed from Cantil Blanco bluff to the shoreline as erosion protection. However, within a few years waves had eroded most of this rock away, and quickly began to undermine the concrete and granite footings of the fort (Golden Gate National Recreation Area 2006). A lighthouse just north of the fort was relocated to the barbette tier of the fort itself after its original location was also undermined by coastal erosion. Much of the brickwork on the seaward faces of the fort continues to be damaged by wind and water exposure (see "Sea Level Rise" section; Golden Gate National Recreation Area 2006).

To combat these natural coastal processes, just as fort construction was nearing completion, engineers were forced to start construction of a 450 m (1,500 ft) seawall to protect the fort (Golden Gate NRA 2006). This project utilized Folsom granite, took eight years to complete, and is considered one of the fort's most outstanding examples of military engineering (Golden Gate NRA 2006). Alas, the seawall was not invincible. Storm waves frequently undercut, displaced, or even crumpled the seawall in places. The seawall has a long and expensive history of repair and maintenance, which continues to this day. In 1981, a large and potentially dangerous undercut cavern was discovered underneath the west end of Marine Drive adjacent to the seawall (Golden Gate NRA 2006).

In the 1860s, as a result of advances in modern long-range artillery, granite and brick style forts became obsolete. Engineers turned to a different battery design, and beginning in 1879, constructed gun batteries of earth and concrete on the hillsides overlooking the fort (Golden Gate NRA 2006).

Geologic Features and Processes

This chapter describes noteworthy geologic features and processes in Golden Gate National Recreation Area, including Fort Point National Historic Site and Muir Woods National Monument.

This chapter of the report focuses on the geologic features and processes that were discussed at the 2007 scoping meeting and during the 2014 conference call, and identified in the GRI GIS data. The discussion is mostly limited to features and processes (and associated map units) that occur within the managed boundary of the park but is expanded to the park's authorized boundaries and beyond where features and processes (and associated map units) have the potential to affect park resources. It should be noted that the extent of GRI GIS data far exceeds the park's boundaries (see posters in pocket).

As described in the "Geologic Setting and Significance" chapter, geologic resources at the park fall into two categories: (1) those associated with the plate tectonic setting, either the ancient convergent boundary (rocks and terranes and the fossils they contain) or the modern transform boundary (San Andreas Fault system), and (2) those associated with surficial features and processes (e.g., landslide deposits, alluvium, and coastal features). This chapter is organized along these lines.

The following are plate tectonic setting related features and processes:

- Rocks of the Franciscan Complex
- Franciscan Terranes
- Franciscan Mélange
- Rocks of the Salinian Complex
- Cenozoic Rocks
- Folds
- Faults
- San Andreas Fault System
- Earthquakes
- Geothermal Systems and Hydrothermal Features
- Paleontological Resources

The following are surficial related features and processes:

- Landslide Deposits and Slope Movements
- Alluvium and Fluvial Processes
- Coastal Features and Processes
- Sea Caves

An abundance of information on the geology of the San Francisco Bay is available in the form of textbooks, guides, journal articles, and webpages. This chapter is a summary of information relevant to resource management and/or interpretation at the park. Please refer to the guidebooks and other references for more detailed information (see "Additional References" section). The source maps for the GRI GIS data also include detailed geologic information, some of which is captured in the ancillary map information document (goga_geology.pdf) available through the NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/App/Portal/Home). Enter "GRI" as the search text and select a park from the unit list. The "Glossary" of this report provides definitions of geologic terms used in the text.

Rocks of the Franciscan Complex

The Franciscan Complex is composed of a great variety of rocks with diverse provenances that came together in an ancient subduction zone (fig. 4; see "Geologic Setting and Significance" chapter; Elder 2013). Befitting a massive agglomeration of rocks, the GRI GIS data differentiates more than two dozen Franciscan Complex map units ("**Kf**" and "**KJf**" units). All three basic types of rocks—sedimentary, igneous, and metamorphic—are present in the Franciscan Complex. Sedimentary rocks are those that formed from the accumulation of sediments. Igneous rocks are those that formed from the cooling of molten material. Metamorphic rocks formed when preexisting rocks were altered, or metamorphosed, by temperature, pressure, and/or hot mineral-rich fluids.

Franciscan rocks originally occurred in the following sequence from bottom to top: (1) igneous rocks of the seafloor—basalt and greenstone; (2) pelagic sedimentary rocks—chert and limestone, and; (3) and clastic, nearshore, sedimentary rocks—graywacke sandstone and shale. The basalt and greenstone rocks originally erupted onto the ocean floor at a mid-ocean ridge (divergent boundary) near the equator as far back as 200 million years ago. They formed the oceanic crust of a tectonic plate moving toward California. As the plate transported the basalt and greenstone, shells of microscopic animals accumulated on top, eventually hardening into either chert or limestone depending on water depth. Nearly 150 million years would pass before some of these rocks reached the subduction zone. Upon their approach, graywacke sandstone and shale deposited by underwater landslides known as turbidity currents capped off the sequence.

The original rock sequence is rarely preserved as a result of complex faulting, folding, and surficial processes. Usually, only one type of rock is visible at the surface or one or more rock types are faulted and smeared together. Though uncommon, enough outcrops that display the original rock sequence are present in the area to make clear their relationship to one another.

Many of the Franciscan rocks were metamorphosed in the subduction zone. Alteration is generally not great; much of the graywacke and chert have been altered by low grade metamorphism. The prefix “meta” is used to indicate a metamorphic rock. For example, “metachert” is metamorphosed chert. Other metamorphic rocks in the Franciscan Complex include the distinctive serpentinite rocks, schist, and various high grade metamorphic rocks.

This section summarizes the prominent rock types of the Franciscan Complex. See Stoffer (2002) for descriptions of the full spectrum of rock varieties of the San Francisco Bay region.

Because of their relatively small areas, tables 1 and 2 list the geologic units mapped within Fort Point National Historic Site and Muir Woods National Monument. The Map Unit Properties Table (in pocket) lists all of the geologic map units mapped within all three park areas.

Table 1. GRI GIS map units within Fort Point National Historic Site.

Map Unit	Rock or Deposit (Age)
Qar	Artificial fill (Quaternary)
Qls	Landslide deposits (Quaternary)
Qsr	Slope and ravine deposits (Quaternary)
Qu	Undifferentiated surficial deposits (Quaternary)
KJfss	Franciscan Complex, sandstone and shale (Cretaceous and Jurassic)
KJfsu	Franciscan Complex, serpentine (Cretaceous and Jurassic)

Table 2. GRI GIS map units within Muir Woods National Monument.

Map Unit	Rock or Deposit (Age)
Qalo	Alluvium, undivided, older (Quaternary)
KJfm	Franciscan Complex, mélange (Cretaceous and Jurassic)
KJfbch	Franciscan Complex, chert and metachert (Cretaceous and Jurassic)

Basalt and Greenstone
Map units **Kfg**, **KJfg**, and **KJfgs**

The base of the Franciscan Complex consists of slightly metamorphosed oceanic crust erupted from ancient submarine volcanoes. The rock basalt comprises the majority of oceanic crust. Basalt is a mafic igneous rock that erupts from volcanoes on the surface or underwater. “Mafic” refers to the high magnesium and iron (ferric) content of minerals in the rock. Most of the Franciscan basalt formed at a mid-ocean ridge representing a divergent boundary (or spreading center) or near a hot spot (upwelling of molten rock from the mantle) that existed thousands of kilometers to the west some 200 million to 100 million years ago (Cretaceous and Jurassic periods) (Shervais 1989; Wahrhaftig and Wakabayashi 1989). When lava erupts under water, contact with the seawater causes the lava to cool rapidly into a distinctive pillow-like shape, which is commonly called “pillow basalt.”

Basalt makes up about 20%–25% of the exposed rocks on the Marin Headlands terrane (Elder 2001). Basalt in the Marin Headlands is typically deeply weathered, forming a zone of orange-brown clays and iron oxides that extends to depths of 5 to 10 m (15 to 30 ft). Where exposed along the coast, the basalt forms hard, erosion-resistant black to dark-green sea cliffs (Elder 2001). Good exposures of pillow basalt occur at Point Bonita on the Marin Headlands (fig. 8).

Greenstone is a form of slightly metamorphosed basalt that has an abundance of greenish, iron-bearing minerals such as chlorite, actinolite, epidote, and pumpellyite. Those minerals typically formed in the presence of seawater as lava cooled underwater into basalt.

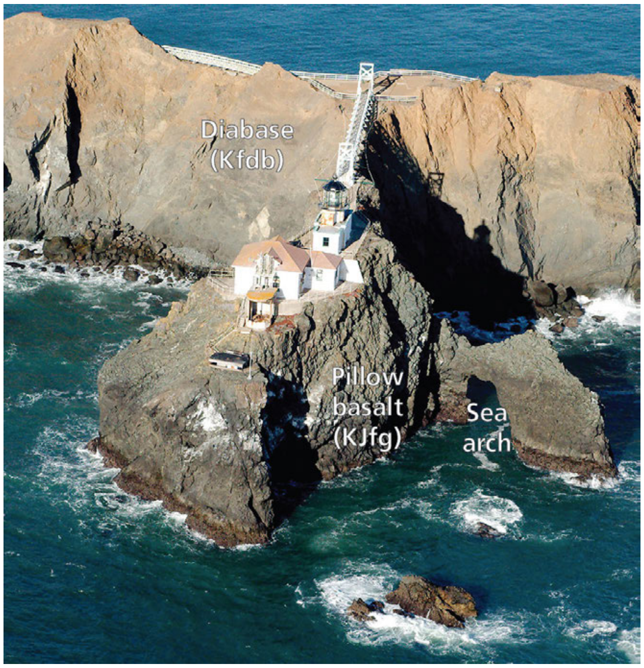


Figure 8. Photograph of pillow basalt and greenstone at Point Bonita. Note how the pillow structure is preserved in the greenstone (KJfg) below the lighthouse. Also note the sea arch to the right of the lighthouse. The rock behind the lighthouse that does not exhibit a pillow structure is diabase (Kfdb). Photograph copyright © 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org, taken 27 September 2013, used with permission.

Although about 10% of the Franciscan Complex is actual greenstone (Sloan 2006), the terms "basalt" and "greenstone" are used almost interchangeably at the park because the rocks are so difficult to distinguish and most basalt has been at least slightly metamorphosed. A good exposure of greenstone occurs along the coastal cliffs near Mori Point (fig. 9).

Small amounts of Franciscan gabbro and/or diabase may occur in association with the basalt and greenstone units. Additionally, non-Franciscan gabbro and diabase (map unit **Kgd**) intruded the Franciscan Complex on Angel Island. Basalt, diabase, and gabbro have similar chemical composition, but differ in texture (crystal size). Basalt is fine-grained. Diabase is typically interpreted in the park as sills or dikes (**Kfdb**) and displays porphyritic texture (large crystals set in a fine-grained matrix) indicating initial slow followed by rapid cooling. Gabbro cools slowly at depth and is therefore coarse-grained.

Figure 9. Photograph of Franciscan limestone and greenstone. Sea cliffs just south of Mori Point (outside of the park's boundary) abruptly transition from greenstone (KJfg; on the left) to limestone (KJfl; on the right). The greenstone is grayish-green on a fresh surface (near the water) whereas the limestone is reddish-brown. The limestone is jagged because of dissolution by seawater; this action may form sea caves. Rockfall debris obscures the contact between the two units. Photograph copyright © 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org, taken 27 September 2013, used with permission.

Chert and Limestone

Map units **Kfl**, **KJfc**, **KJfl**, and **KJfbch**

The Marin Headlands contain one of the longest stratigraphic sequences of chert in the world. Chert is a fine-grained, hard, and extremely erosion-resistant sedimentary rock composed almost entirely (>93%) of silica. It is commonly associated with deep ocean settings. Chert was probably deposited atop cooled ocean crust (basalt) that had migrated away from the spreading center (see "Basalt and Greenstone" section) into deeper water, yet far enough away from shore not to receive sand, clay, or silt sediments from terrestrial sources (Stoffer 2002).

In the park, much of the chert is derived from layered deposits of microscopic marine organisms called radiolarians which secrete intricate "skeletons" made of silica (SiO_2). When they die, their skeletons slowly accumulate on the ocean floor and harden into chert. A layer of radiolarian chert only one millimeter thick takes about 1,000 years to accumulate. Based on the ages of the oldest (200 million years old) and youngest (100 million years old) radiolarian fossils in the Franciscan chert, the sequence represents 100 million years of deposition (Murchey 1984; Wahrhaftig and Murchey 1987).

Most Franciscan chert is reddish-brown and less commonly green, gray, or white (Goldman 1959). The different colors suggest relative levels of oxygen during deposition. Red commonly results from the oxidation of iron in an oxygen-rich environment; green commonly results from reduction of iron in an oxygen-poor environment.

Most of the Franciscan chert exposed in the park occurs in distinct, thin (3–13 cm [1–5 in]) layers alternating with even thinner shale layers (up to 2.0 cm [0.8 in]) (Schlocker et al. 1958). Deposits of these alternating layers are called "ribbon chert" and represent changing proportions of silica-rich sediments. When the chert and shale sediments were initially deposited, the layers were not so distinct. As the layers became buried, the pressure of the overlying material concentrated the silica-rich sediment into distinct layers which are much harder than the shale layers. Over time, the shale erodes, leaving pronounced chert layers. Exceptional exposures of ribbon chert occur along Conzelman Road (see "Marin Headlands Terrane" and "Folds" sections; fig. 10).

Not all of the chert in the park is ribbon chert. In some places layers of chert are more than 3 m (10 ft) thick (Goldman 1959). These are zones of jasper or metachert and reflect hydrothermal activity both near the mid-ocean ridge and in the subduction zone (James Hein, US Geological Survey, personal communication, 2012, cited in Elder 2013b, p.7). Excellent examples of a thick localized unit of chert occur on the Marin Headlands, where relatively hard deposits of chert and metachert support prominent ridges (Schlocker et al. 1958).

Figure 10. Photograph of chevron folds in radiolarian chert. These folds are visible along Conzelman Road in the Marin Headlands. National Park Service photograph from 2007 GRI scoping meeting.

Limestone is a carbonate sedimentary rock. Unlike chert, which is commonly deposited in deep ocean water, limestone is commonly deposited in shallow marine settings. Changing water depths or ocean temperatures may result in alternating layers of chert and limestone (Stoffer 2002). Limestone may have been deposited in the shallow water surrounding volcanoes or other uplifts near the mid-ocean ridge (divergent plate boundary) where the basalt was forming (Stoffer 2002).

Graywacke and Shale

Map units **Kfgwy**, **KJfss**, **KJfcg**, **KJsk**, **KJfmss**, **KJfsh**, and **KJfbss**

Graywacke (including metagraywacke) may be the most abundant rock type in the San Francisco Bay region (Stoffer 2002). About 80% of the Franciscan Complex consists of graywacke and shale (Stoffer 2002; Sloan 2006). The amount of graywacke and shale that was originally deposited is staggering. According to Sloan (2006), more than enough Franciscan graywacke and shale accumulated during Mesozoic subduction to bury the entire state of California to a depth of more than 3,000 m (10,000 ft), which equates to roughly 1.5 million cubic kilometers (350,000 cubic miles).

Graywacke is a variety of gray, clay-rich ("impure" or "dirty") sandstone. It consists of a poorly sorted (variety of sizes) mixture of angular rock and mineral fragments. Franciscan graywacke deposits typically contain shale layers and rarely conglomerate. Graywacke, shale, and conglomerate are all clastic rocks, meaning they were derived from fragments of preexisting rocks ("clasts"). Fragments of andesitic volcanic debris in the Franciscan graywacke are what give it its characteristic greenish-gray color (Elder 2001).

Graywacke is commonly thought to represent a marine environment where erosion, transportation, deposition, and burial of sediment were so rapid that complete chemical weathering did not occur and many clay and rock fragments remain. About 100 million years ago in the San Francisco Bay Area, an environment like this likely existed adjacent to the subduction zone. Streams draining an ancient volcanic mountain range dumped

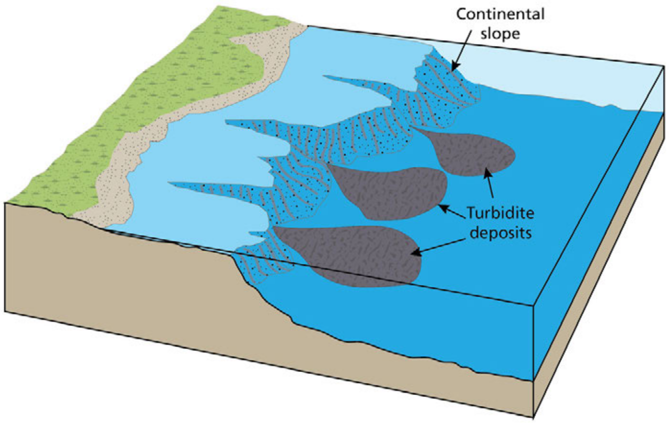


Figure 11. Illustration of turbidite formation. Turbidites form when terrestrial sediments tumble from the top of the steep continental slope into deep water in a density-driven underwater landslide. Turbidites would eventually lithify into the graywacke and shale of the Franciscan Complex. Turbidites typically display a fining-upward sequence known as graded bedding. Graphic by the author after Tarbuck et al. (2011).

Figure 12. Photograph of graywacke turbidite cliffs north of Rodeo Beach. Photograph copyright © 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org, taken 27 September 2013, used with permission.

large quantities of poorly sorted sediments into an ocean basin (fig. 4; Stoffer 2002). As the sediment accumulations became thicker, they became less stable under their own weight and tumbled down the steep continental slope in an underwater, density-driven landslide known as a turbidity current. This movement could also have been triggered by an earthquake. The material came to rest on top of radiolarian chert at the bottom of the continental slope in a deep oceanic trench. This deposit, called a turbidite (fig. 11), would eventually lithify into the graywacke and shale of the Franciscan Complex.

Turbidites typically display graded bedding. As a turbidity current flows into a trench, the largest sediments settle out first followed by finer particles, producing a fining-upward sequence known as graded bedding. Rocks formed out of a turbidite deposit will consist of larger grained rocks like conglomerate and coarse sandstone at the base, transitioning upwards into fine-grained sandstone and finally shale. Often times, turbidite deposits will form on top of each other and the resulting rocks will be a series of alternating shale (fine) and sandstone (coarse) layers.

Graywacke tends to crop out along beaches and ridges. An exceptional cliff exposure of graywacke and shale turbidites occurs near Rodeo Beach in the Marin Headlands (fig. 12; Stoffer 2002). The south end of Baker Beach in the Presidio is a great place to see graded bedding with a lot of shale; the north end of Baker Beach has mostly sandstone and a little shale (Will Elder, park ranger, Golden Gate National Recreation Area, written communication, 30 October 2015). Conglomerate is rare, but has been noted at Bonita Cove and on Wolf Ridge (Wahrhaftig 1984). The graywacke exposed at Baker Beach is riddled with tafoni—honeycomb-like structures produced by physical and chemical weathering in salt-rich environments such as intertidal areas and deserts (fig. 13).

Figure 13. Photograph of tafoni weathering. The graywacke at Baker Beach exhibits tafoni—honeycomb-like structures produced by physical and chemical weathering in intertidal areas. National Park Service photograph, available at http://www.nps.gov/goga/learn/education/graywacke-sandstone-faq.htm.

Figure 14. Photograph of serpentinite cliffs between Fort Point and Baker Beach. Serpentinite in the park is soft and commonly highly sheared, making it susceptible to landslides. Several landslide scars are visible on the left side of the photograph (dashed lines). Photograph copyright © 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org, taken 27 September 2013, used with permission.

Serpentinite
Map units **KJfsu** and **KJspm**

Serpentinite is a metamorphic rock composed of the serpentine minerals antigorite, lizardite, and sometimes chrysotile. In fibrous form, chrysotile is the most common type of naturally occurring asbestos (see "Naturally Occurring Hazardous Materials" section). Nearly half of the serpentinite in North America is located in California—it is the state rock—and it is fairly common throughout the San Francisco Bay Area. The name refers to the often green mottled color which resembles reptilian skin. Serpentinite is a heavy, dark rock that is waxy, greasy, or silky in texture.

Most of the serpentinite in the San Francisco Bay Area is derived from the Coast Range ophiolite which is a piece of oceanic crust underlying rocks of the Great Valley sequence (see "Plate Tectonic Setting" section). Peridotite rocks of the Coast Range ophiolite were metamorphosed by hydrothermal activity in the subduction zone and rose toward the surface (as a result of their lower density) along regional thrust faults associated with subduction (California Geological Survey 2002). On rare occasions the serpentinite rocks were accompanied by high grade metamorphic rocks (see "High Grade Metamorphic Rocks" section).

Blocks of serpentinite now occur within terrane suture zones known as mélange (see "Franciscan Mélange" section; Irwin 1990). Because serpentinite is relatively soft, it is easily deformed and therefore sheared in most places as a result of crustal disturbances associated with faulting (Schlocker et al. 1958, Irwin 1990). In the park, serpentinite is mapped at Fort Point, the Presidio, and in shear zones associated with the landslide west of Land's End (Schlocker et al. 1958). Serpentinite is often exposed on coastal bluffs with good exposures between Fort Point and Baker Beach (fig. 14). The Presidio's website, http://www.nps.gov/prsf/planyourvisit/baker-beach.htm, states that "the best views of San Francisco's serpentine cliffs are from the overlooks on Lincoln Boulevard, north of Baker Beach."

High Grade Metamorphic Rocks
Map units **KJfsch**, **KJfbsch**, **KJfbm**, **KJfbmg**, **KJfmgs**, **KJfmch**, and **KJfmgc**

Most metamorphic Franciscan rocks are low or medium grade, such as slightly metamorphosed graywackes with blueschist-facies minerals (Elder 2013). In some places, however, areas of high grade metamorphic rocks reflect high pressure and medium- to high-temperature regimes (Elder 2013). Such conditions were only present during the earliest phases of subduction, when the rocks of the subducting plate first came in contact with hot rocks in the mantle (Sloan 2006). The minerals in high grade metamorphic rocks have been altered into entirely new minerals. The resulting rocks include blueschist (present in map units **KJfsch** and **KJfbm**), amphibolite (present in **KJfbmg**, **KJfmgs**, **KJfmch**, and **KJfmgc**), and eclogite (present in **KJfbmg**) (Sloan 2006; Elder 2013).

Chunks of these rocks are often found "floating" in the mélange of the Franciscan Complex or surrounded by serpentinite (Pampeyan 1994; Stoffer 2002; Sloan 2006). Their presence at the surface suggests a complex chain of events: forming as oceanic crust, very deep burial and metamorphosis, thrusting back to the surface along faults (Stoffer 2002).

Hydrothermal Areas

Map unit **KJfbsc**

Hydrothermal deposits and hydrothermally altered rocks, though not technically part of the Franciscan Complex, are included here because in the area of the park they occur solely in association with Franciscan

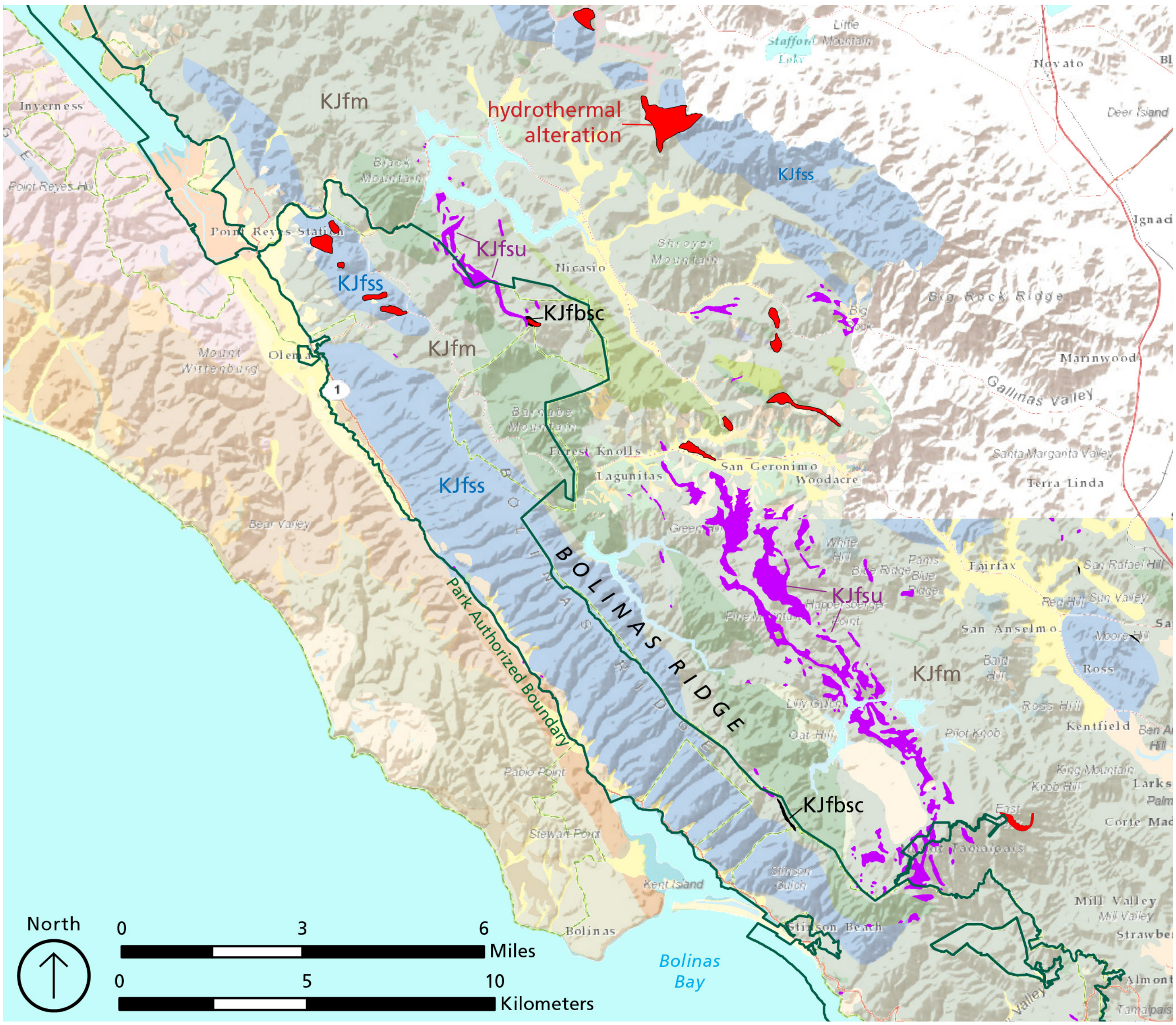


Figure 15. Map of hydrothermal areas in the vicinity of Golden Gate National Recreation Area. Hydrothermal deposits and alteration occur in shear zones associated with Franciscan rocks and where serpentinite has been altered by hydrothermal activity. Areas of hydrothermal alteration are solid red. Silica carbonate rocks (KJfbsc) are solid black. Serpentinite (KJfsu) is solid purple. KJfss indicates Franciscan sandstone and shale. KJfm indicates mélange. The green line is the park's authorized boundary. The translucent background is the GRI GIS data for the park (see posters, in pocket). Basemap is ESRI "World Terrain Base" layer (accessed 16 May 2016).

rocks, most often serpentinite (**KJfsu**). "Hydrothermal" refers to deposits that occur where fluids are released from magma or heated rock. These deposits form along faults and fractures in bedrock. Chemical conditions of the fluids change as they interact with the bedrock, and minerals are either dissolved or precipitated (Stoffer 2002).

In some places in the San Francisco Bay region ore minerals of mercury, manganese, magnesium, copper, lead, and other metallic and non-metallic minerals were deposited hydrothermally (Stoffer 2002). The mineral cinnabar, an ore of mercury, is an economically important hydrothermal deposit in the San Francisco Bay region (see "External Energy and Mineral Development" section; Stoffer 2002).

In the GRI GIS data, hydrothermal deposits include the map unit silica-carbonate rocks (**KJfbsc**) and the GIS feature class "area of hydrothermal alteration." In the park, these deposits are mapped north and east of Bolinas Ridge (fig. 15). Silica-carbonate rocks are found in fissures and along the margins of serpentinite (**KJfsu**). The silica-carbonate rock was produced when hydrothermal activity in shear zones altered some of the serpentinite to silicate minerals such as chalcedony, opal, and quartz and carbonate minerals such as calcite (Schlocker et al. 1958).

The GIS feature class "area of hydrothermal alteration" occurs within units of Franciscan graywacke sandstone and shale (**KJfss**) and mélange (**KJfm**). Some of these areas are related to volcanic activity, such as dikes and other intrusive igneous rocks much younger than the Franciscan rocks. For example, specimens of the mineral adularia from Bolinas Ridge have been dated to about 13 million or 12 million years ago (Miocene Epoch) and relate to the migration of the San Andreas Fault through the region (McLaughlin et al. 1996).

Franciscan Terranes

Franciscan Complex rocks ("**Kf**" and "**KJf**" units) are assigned to terranes; each represents a period of accretion onto the North American continent. Accretion occurred episodically beginning about 160 million years ago until about 50 million years ago (see "Plate Tectonic Setting" section; Elder 2013). The terranes are differentiated based on age, composition, tectonic history, and metamorphic grade and are separated from one another by mélange

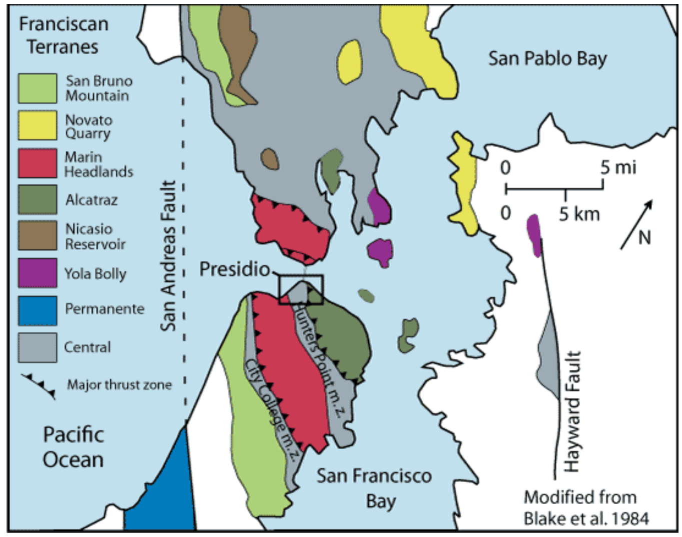


Figure 16. Map of Franciscan Complex tectonic terranes. This map shows the seven terranes of the Franciscan complex which are mapped in the park and the mélange ("Central terrane") that separates them. Each terrane represents a period of accretion and is characterized by a specific history of rock deposition and degree of metamorphism. Graphic modified by Will Elder (National Park Service) from Blake et al. (1984), available at https://www.nps.gov/prsf/learn/nature/terrane-map.htm.

(see "Franciscan Mélange" section). The structurally highest terranes (in the east) are the oldest; each major thrust wedge to the west is younger (Blake et al. 1984; Wakabayashi 1992).

Geologists grouped Franciscan Complex rocks into roughly 10 terranes, although which rocks are assigned to which terrane and how many terranes exist depends on interpretation. Seven of these terranes—Yolla Bolly, Nicasio Reservoir, Alcatraz, Marin Headlands, Permanente, Novato Quarry, and San Bruno Mountain—are mapped in the park (fig. 16).

Yolla Bolly Terrane

The Yolla Bolly terrane is the easternmost and oldest of the Franciscan terranes (Blake et al. 1984). U-Pb dating of detrital zircon yielded a maximum depositional age of 102 million years for clastic sediments (Snow et al. 2010). Prior to this analysis, fossils indicated a much older middle- to late-Jurassic age (Sliter et al. 1993; Crawford 1976; Elder and Miller 1990). These older Jurassic fossils apparently were reworked into mid-Cretaceous trench sediments of this terrane (Dumitru 2012).

Based on the terrane map by Brabb et al. (2000), the Yolla Bolly terrane occurs in the northern and eastern Bay Area (fig. 16). It is mapped as metamorphic rocks (metabasalt, metachert, and metagraywacke). The Yolla Bolly terrane is also mapped on Angel Island, where Wakabayashi (1992) referred to it as the Angel Island nappe. Serpentinite is common where the unit is severely sheared (Blake et al. 2000).

The standard Franciscan sequence of rocks—basalt or greenstone, chert and/or limestone, graywacke and shale—is exhibited by some of the rocks of the Yolla Bolly terrane. The area has been affected by repeated "knife-sharp" thrust faults and tight folds that can give the appearance that the graywacke and chert are interbedded (Blake et al. 2000). Much of the basal greenstone has been removed by faulting (Blake et al. 2000).

Areas of severely sheared rock and metagraywacke in the Yolla Bolly terrane weather to soft vermiculite which produces subdued topography (Blake et al. 2000). These areas are prone to landslides, but occur in a remote region of the park where they are unlikely to pose great risk (refer to "Slope Movements Hazards and Risks" section). The harder metagreenstone generally forms rugged mountains (Blake et al. 2000).

Nicasio Reservoir Terrane

Unlike the other terranes within the park, the Nicasio Reservoir terrane is primarily igneous rocks (pillow basalt and gabbro) with only minor amounts of radiolarian chert (Blake et al. 2000). It is mapped from Muir Woods National Monument northwest to the Nicasio Reservoir (fig. 16). The rocks likely represent a Late Jurassic–Early Cretaceous oceanic island similar to Hawaii that formed about 20° to the south, traveled to its present position, and accreted to North America after Early Cretaceous time (Blake et al. 2000).

Alcatraz Terrane

The Alcatraz terrane is characterized by thick-bedded graywacke turbidites. Within the park, the Alcatraz terrane is found on Alcatraz Island where it is mapped as sandstone and shale (**KJfss**, **KJfmss**; fig. 17). Outside of the park, it is mapped on Yerba Buena Island and under much of northeastern San Francisco. The rocks of the Alcatraz terrane are severely sheared but distinguishable from Franciscan mélange because the Alcatraz terrane lacks blocks of vastly different rock

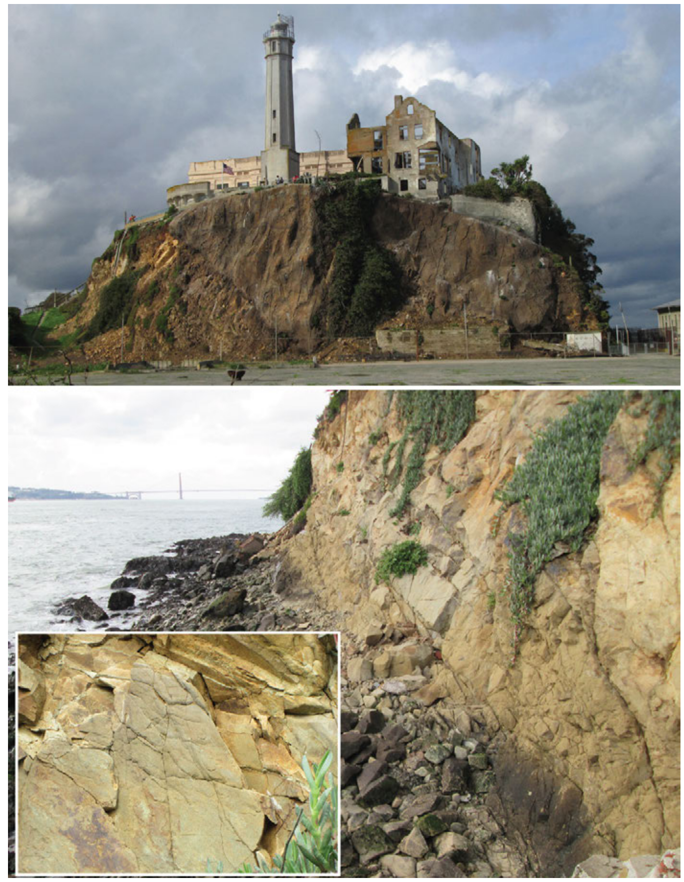


Figure 17. Photographs of Alcatraz terrane rocks. The Alcatraz terrane is dominated by thick-bedded turbidites, primarily sandstone and shale, and is severely sheared (see inset photograph). It is differentiated from the other terranes by the lack of other Franciscan rocks such as basalt, greenstone, chert, and limestone. Photographs by John Graham (Colorado State University), taken December 2014.

types, such as basalt, greenstone, chert, or limestone, which characterize the Franciscan terrane (see "Franciscan Mélange" section; Blake et al. 2000; Wagner et al. 2006). Molluscan fossils (see "Paleontological Resources" section), which are very unusual in Franciscan graywacke, suggest that the sediments were deposited between 140 million and 130 million years ago (Elder 1998). However, Snow et al. (2010) reported detrital zircon ages of 100 million years for this terrane.

Marin Headlands Terrane

The Marin Headlands terrane bisects the San Francisco Peninsula, spans the Golden Gate, and underlies much of the rugged topography in the Marin Headlands. The terrane includes mélange and all of the rock types typical of the Franciscan Complex: basalt or greenstone,

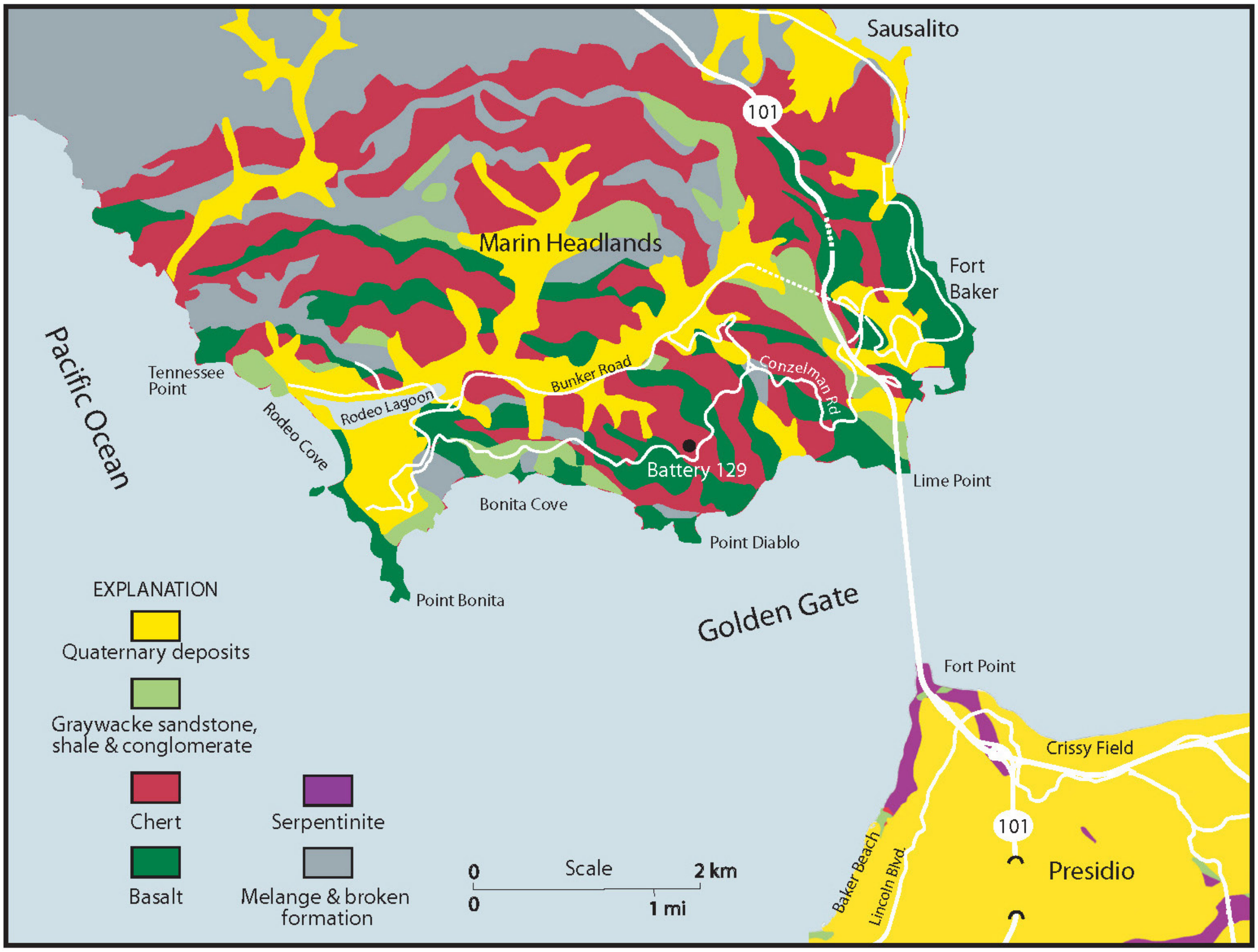


Figure 18. Geologic sketch map of the Marin Headlands terrane. The rocks consist of basalt overlain by chert which is overlain by graywacke. Resistant chert makes up ridges (red areas on map). Ribbon chert exposed along Conzelman Road was deformed into spectacular chevron folds (fig. 10). Refer to the map poster (in pocket) for a more detailed map. National Park Service map, available at http://www.nps.gov/goga/learn/education/geology-resources.htm.

serpentinite, chert and limestone, and graywacke and shale deposited in turbidites (fig. 18). Metamorphic rocks including blueschist, amphibolite, and eclogite are also present but in much lesser amounts. An excellent example of internal thrust faults within a terrane can be found in the Marin Headlands, where the stratigraphic sequence (basalt, chert, graywacke) is wholly or partially repeated at least 11 times (Wahrhaftig 1984).

Chert (**KJfbch**) in this terrane is particularly noteworthy, as it underlies between one-third and one-half of the Marin Headlands and forms all the major ridges (see poster in pocket; Schlocker et al. 1958). The folded and faulted ribbon cherts are spectacularly exposed along Conzelman Road where they are a popular stop for visitors and geology field trips (fig. 10). Chert is also exposed between layers of pillow basalts near the Point Bonita tunnel; chert deposition indicates long periods of time between some of the volcanic eruptions (Murchey and Jones 1984; Hagstrum and Murchey 1993).

Fossils (see the “Paleontological Resources” section) indicate the oceanic rocks (basalt and chert) of the Marin Headlands terrane range in age from about 200 million to 100 million years old, when the rocks were in the open ocean (Blake et al. 2000; Murchey and Jones 1984). The fossils indicate a tropical depositional environment, likely near the equator (Murchey and Jones 1984). The overlying turbidite deposits formed between about 100 million and 90 million years ago when the rocks were closer to the subduction zone (Blake et al. 2000; Murchey and Jones 1984).

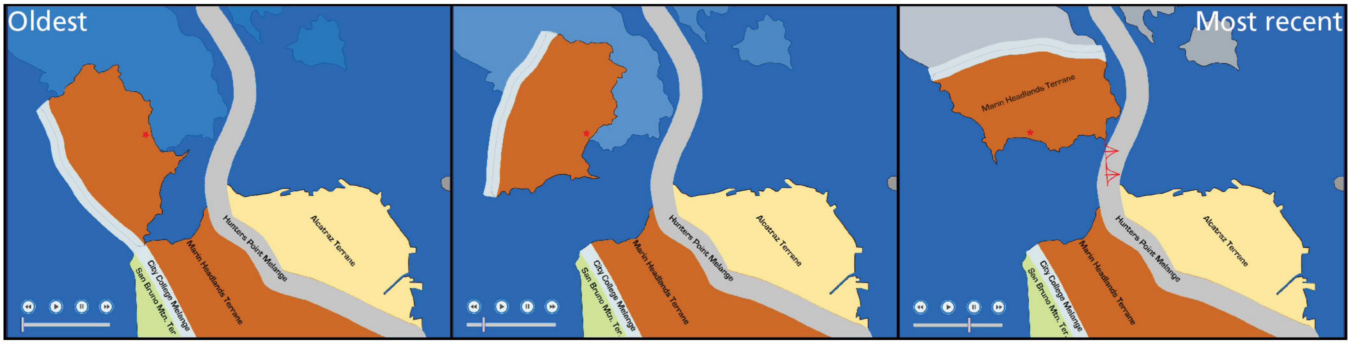


Figure 19. Illustration of the Marin Headlands terrane rotation. The Marin Headlands terrane north of the Golden Gate rotated clockwise about 130° (Curry et al. 1984; Wahrhaftig 1984; Wakabayashi 1999b). The graphics progress from oldest (left) to most recent at the right. The timing of rotation is poorly constrained, but postdates emplacement of Franciscan rocks in the Bay Area (Elder 2013). Screenshots from a National Park Service animation, available at http://www.nps.gov/goga/learn/education/headlands-animation.htm.

The terrane accreted onto North America close to the present latitude of Mexico about 95 million years ago (Hagstrum and Murchey 1993). The terrane was then transported northwest along the coast by oblique subduction before the San Andreas Fault system took over northward transport. Additionally, the portion north of the Golden Gate rotated clockwise about 130° (fig. 19; Curry et al. 1984; Wahrhaftig 1984; Wakabayashi 1999b; Elder 2001). The timing of rotation is poorly constrained but postdates emplacement of Franciscan rocks in the area (Elder 2013). This degree of rotation on such a large fault block is not documented in the other Franciscan terranes.

Permanente Terrane

In the area of the park, the Permanente terrane is found mainly as small blocks smeared along the San Andreas Fault. Rocks of the Permanente terrane are primarily basalt overlain by small amounts of Lower Cretaceous radiolarian chert, blocks of limestone, and some graywacke (Murchey and Jones 1984; Sliter 1984; Elder 2013). The basalt and chert were likely deposited near seamounts (underwater mountains, typically extinct volcanoes) close to the equator (Blake et al. 1984; Tarduno et al. 1985).

North of the Golden Gate, Permanente terrane consists of blocks of gray limestone (**Kfl**) north of Bolinas, and greenstone and diabase (**KJfg**, **Kfdb**) on Point Bonita (Blake et al. 2000). South of Golden Gate, the terrane is west of the San Andreas Fault near the park areas of Mori Point, Milagra Ridge, Sweeney Ridge, Rancho Corral de Tierra, and the Phleger Estate (Blake et al. 1984). In those park areas, it is mainly mapped as sandstone and shale (**KJfss**), and greenstone (**KJfmgs**). Smaller areas of chert (**KJfc**) and limestone (**Kfl** and **KJfl**) are also present; the limestone is similar in composition and microfossil content to the limestone near Bolinas (Sliter 1984). Some serpentinite (**KJfsu**) is mapped in this terrane in or along faults and shear zones (Pampeyan 1994).

Novato Quarry Terrane

The Novato Quarry terrane is primarily composed of turbidites and massive sandstone (Blake et al. 1984). Until recently this terrane was not thought to occur in the park. Detrital zircon ages were calculated for rocks sampled at Land's End and along Bolinas Ridge—areas that were formerly mapped as the San Bruno Mountain terrane. The minimum zircon ages for both of these areas came out between 86 million and 81 million years. Because the minimum zircon ages for the San Bruno Mountain terrane in this area is 52 million years, the sandstones at Land's End and Bolinas Ridge are now interpreted to belong to the Novato Quarry terrane (Will Elder, park ranger, Golden Gate National Recreation Area, written communication, 30 October 2015).

San Bruno Mountain Terrane

The San Bruno Mountain terrane is mapped along Bolinas Ridge in the park (fig. 16). It is primarily composed of sandstone and some shale turbidites (**KJfss**). Granite weathered from the ancient Sierra Nevada mountain range is the likely sediment source for the turbidites (Konigsmark 1998). Fossils have not been found in the terrane; metamorphism and hydrothermal mineral veins (see "Hydrothermal Areas" section) may have destroyed any fossils that were originally preserved (Blake et al. 2000). Detrital zircon dating indicates a maximum age of 52 million years (Snow et al. 2010).

Franciscan Mélange

Map unit **KJfm**

Zones of mélange separate the Franciscan terranes in the San Francisco Bay Area (fig. 16). In some publications the mélange north of the Golden Gate may be referred to as the "Central terrane" (e.g., Blake et al. 1982, 1984; Elder 2013). South of the Golden Gate, the Hunter's Point mélange zone separates the Marin Headlands and Alcatraz terranes and the City College mélange zone separates the Marin Headlands and San Bruno Mountain terranes. Mélange (**KJfm**) underlies nearly all of Muir Woods National Monument and the Hunter's Point mélange zone is mapped beneath the surficial deposits of Fort Point National Historic Site.

During accretion and later faulting, some of the Franciscan rocks were "thoroughly ground up" into mélange (Sloan 2006). The mélange consists of a relatively soft crushed argillite and shale matrix supporting blocks of Franciscan rocks of any type (e.g., graywacke, chert, or greenstone) "floating" in the matrix (fig. 20). These blocks range in size from small, a meter (few feet) across, to huge, many square kilometers (miles) in area (Sloan 2006). Serpentinite and high grade metamorphic rocks are also found in the mélange (Blake et al. 2000). The soft and sheared mélange forms rounded hills (mainly shale and serpentinite) among scattered blocks of harder Franciscan rocks (Sloan 2006).

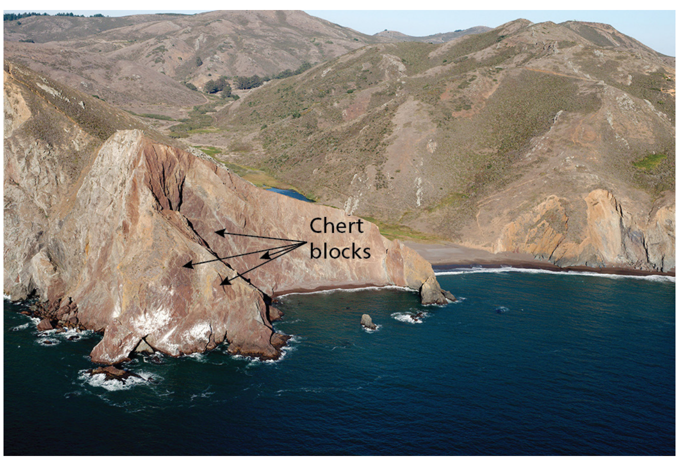


Figure 20. Photograph of Franciscan mélange at Tennessee Cove. Franciscan mélange consists of blocks of Franciscan rocks of any type surrounded by a matrix of sheared, soft shale. Massive blocks of chert (reddish rock in photograph) are in the mélange (KJfm) mapped at Tennessee Cove. Photograph copyright © 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org, taken 27 September 2013, used with permission.

Although the mélange is sometimes considered a single "terrane" (e.g., "Central terrane"), it is not a true terrane. As described by Blake et al. (2000), the mélange is the product of tectonic mixing (see Wakabayashi 2011) of rocks derived from several terranes: (1) the rocks that would form the matrix from an unnamed and almost completely disrupted terrane, (2) the chert, greenstone, graywacke, and metamorphic blocks from accreted Franciscan Complex terranes, and (3) the serpentinite from the Coast Range ophiolite. The original sedimentary deposits that became the mélange matrix are not well preserved anywhere, although an abandoned quarry near Greenbrae may display some of those layers (Blake et al. 2000). Another theory proposes that the mélange is the result of gravity slumping and mixing on the slope leading into the trench (Aalto 1989; Will Elder, park ranger, Golden Gate National Recreation Area, written communication, 30 October 2015). Both gravity and tectonic mixing may have taken place in the Franciscan mélange.

Fossils (see "Paleontological Resources" section) suggest an age between about 160 million and 100 million years old (Blake and Jones, 1974; Murchey and Jones, 1984). The radiolarian fossils in the cherts of the matrix and the Franciscan blocks are of similar age but different assemblages. Radiolarians in the blocks are similar to those of the Marin Headlands, meaning those blocks were originally associated with that terrane (Blake et al. 2000). The radiolarians in the matrix may have been from some kind of deep-water, continental margin deposit into which the other terranes were accreted or dispersed (Blake et al. 2000).

Rocks of the Salinian Complex

Map units **Kg**, **Kgri**, **Kgdt**, and **Kgr**

Cretaceous intrusive igneous rocks of the Salinian complex form the basement west of the San Andreas Fault, with prominent exposures at Point Reyes, Inverness Ridge, and Montara Mountain (Stoffer 2002). These rocks are strikingly different from those of the Franciscan Complex on the other side of the

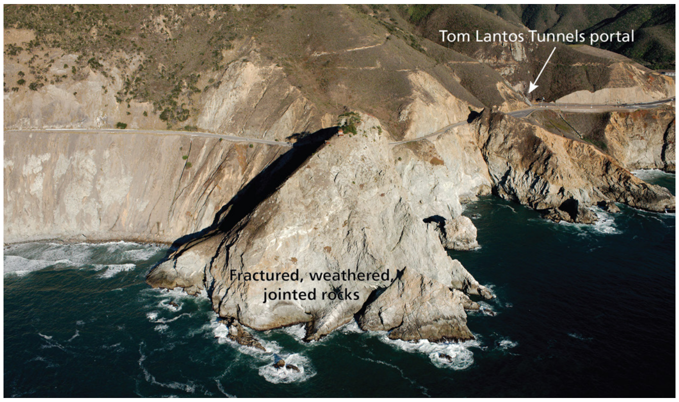


Figure 21. Photograph of Salinian granite sea cliffs. Granitic rocks of Montara Mountain (Kgr) form sea cliffs south of the Devil's Slide area. The granite is heavily fractured and weathered and jointing is visible, especially in the rocks in the foreground. The entrance to the Tom Lantos Tunnels, which allows travelers to bypass the hazardous Devil's Slide area, is visible in the upper right portion of the photograph. Photograph copyright © 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org, taken 27 September 2013, used with permission.

fault. Salinian rocks are primarily granodiorite, with lesser amounts of granite and tonalite. Granodiorite, granite, and tonalite are felsic (containing light-colored minerals), thus providing contrast to the mafic Franciscan Complex across the fault.

The granite of Montara Mountain (**Kgr**) is the only Salinian unit mapped in the park; the remaining units (**Kg**, **Kgri**, **Kgdt**) are mapped on the Point Reyes Peninsula. In the park, **Kgr** is mapped in the Devil's Slide area (south of Point San Pedro) and also underlies most of Rancho Corral de Tierra. The granite is heavily fractured and weathered. Along the coast it forms sea cliffs where jointing may be visible and major landslides have occurred (fig. 21). In Rancho Corral de Tierra, shallow landslides are abundant in areas of weathered granite called grus (Pampeyan 1994). See the "Slope Movements" section in this chapter for more information about landslides.

Cenozoic Rocks and Deposits

Map units **Qc**, **Qoc**, **Qml**, **Qfr**, **QTs**, **QTsc**, **QTm**, **Tps**, **Twg**, **Tsc**, **Tsm**, **Tm**, **Tls**, **Tbv**, **Tlo**, **Tlss**, **Tla**, **Tmb**, **Tvq**, **Ta**, **Tb**, **Tw**, **Tpr**, **Tsu**, and **Tsl**

During the Cenozoic Era, tectonism in the San Francisco Bay Area evolved from a subduction to a transform regime (see "San Andreas Fault" section and "Geologic History" chapter) and the rocks deposited during this time reflect this complex transition. Tension, compression, and localized faulting associated with the development of the San Andreas Fault broke the pre-Cenozoic bedrock into blocks which "bobbed" up and down independently of each other creating basins and uplifts (Argus and Gordon 2001). The San Francisco Bay block is one such block; it was a structural high (uplift) and therefore subject to erosion until about 3 million years ago. Today, it is stable or slowly subsiding (Elder 2013). As the uplifted blocks eroded, sediments accumulated in basins created by the down-dropped blocks. The location and size of the basins evolved throughout the early Cenozoic Era as the basement blocks continued to rise and/or fall due to tectonism. Most of the Tertiary rocks in the park were deposited in these successor basins and are separated by unconformities (Elder 2013). Cenozoic deposits also may reflect changes in sea level (Moxon 1988).

The Cenozoic Era covers the timespan from 66 million years ago to present day. It is divided into the Paleogene and Neogene periods (formerly Tertiary; "**T**" map units) and the Quaternary Period ("**Q**" map units) (fig. 3; table 3). Cenozoic units in the GRI GIS data are sedimentary with the exception of two volcanic units: Burdell Mountain volcanics (**Tbv**) and Mindego basalt (**Tmb**). Burdell Mountain volcanics consist of 11-million-year-old andesite flows and breccia, dacite flows, and rhyolite, which were displaced from the Quien Sabe volcanics and formed behind the northwest migrating Mendocino triple junction (Wagner et al. 2011). The Mindego basalt consist of flow breccia, tuff, pillow basalt, and flows west of the San Andreas Fault (near Half Moon Bay) and are thought to represent a volcanic center that erupted 25 million–20 million years ago (Stanley et al. 2000). The remaining Cenozoic rocks are primarily conglomerate ("consolidated gravel") or sandstone ("consolidated sand") and range from marine to coastal to nonmarine (e.g., alluvial) origins (Stoffer 2002). Refer to the Map Unit Properties Table and Elder (2013) for complete lithologic descriptions.

Many of the Tertiary rocks have been sliced up and displaced along faults of the San Andreas Fault system (Elder 2013). At the beginning of the Cenozoic Era (66 million years ago), Franciscan-style subduction was still occurring. It lasted until at least 15 million years ago when a switch to transform movement began to transport rocks on the west side of the San Andreas

Table 3. Geologic age and description of Cenozoic units mapped in Golden Gate National Recreation Area.

Era	Period	Epoch	Age*	Unit	Description
Cenozoic	Quaternary	Holocene	0.01–present	Qar, Qya, Qbs, Qhb, Qdsy, Qmf, Qyl, Qf1, Qbmy, Qafy, Qaly	Artificial fill, stream channel deposits, beach sand, basin deposits, dune sand, landslide deposits, bay mud, and alluvial fans
		Holocene / Pleistocene		Deposits: Qalo, Qbmo, Qls, Qsr, Qob, Qc, Qu, Qcl, Qpaf1, Qol Named units: Colma Formation (Qc)	Stream channel deposits, bay mud, landslide deposits, slope and ravine debris, beach sand, colluvium, and stream terrace deposits Sand with silt, clay, and gravel interbeds
		Pleistocene	2.6–0.01	Deposits: Qoal, Qtmr Named units: Olema Creek Formation (Qoc), Millerton Formation (Qml)	Stream channel and marine terrace deposits Granitic sand and gravel interbedded with mud and peat Stream terrace deposits
		Pleistocene / Pliocene		Santa Clara Formation (QTsc) Merced Formation (QTm Purisima Formation (Tps)	Conglomerate derived from the Franciscan Complex, siltstone, and fine-grained sandstone
	Tertiary: Neogene	Pliocene	5.3–2.6		
	Tertiary: Neogene	Miocene	23–5.3	Monterey Group (Tm)	Siliceous shale and arkosic sandstone
	Tertiary: Paleogene	Oligocene	34–23	Units of this age interval are not mapped in the park.	
	Tertiary: Paleogene	Eocene	56–34	Whiskey Hill Formation (Tw) Butano Sandstone (Tb)	Sandstone and claystone turbidites
	Tertiary: Paleogene	Paleocene	66–56	Tsu, Tsl	Sandstone, shale, and conglomerate turbidites

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

Colors are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps. See the Map Unit Properties Table (in pocket) for more detail.

Fault to the north. This process brought Cenozoic rocks from the south to the area of the park. Rocks 15 million years old and older have been transported the farthest north, while rocks and deposits 15 million years old and younger have been transported progressively less. Offset of the Merced and Santa Clara formations along the San Andreas Fault is clearly visible on the map (see poster in pocket).

All Paleogene units mapped in the park are related to the development of turbidites. Except for the Whiskey Hill Formation (**Tw**), they are mapped only on the west side of the San Andreas Fault. These rocks west of the San Andreas Fault originated to the south and were transported to their current location by movement along the fault. A Paleocene turbidite sequence (**Tsu**, **Tsl**), which overlies the Cretaceous Montara quartz diorite (**Kgr**), is well exposed at Point San Pedro (fig. 22; Morgan 1981), and the submarine fan deposits of the Butano Sandstone (**Tb**) underlie most of the Phleger Estate (Critelli and Nilsen 1996). According to the GRI GIS data, the Phleger Estate is underlain by the Whiskey Hill Formation (**Tw**). Recent detrital zircon ages, however, have shown that these rocks are better correlated with the Butano Sandstone (**Tb**) (Russel Graymer, US Geological Survey, research geologist, email communication, 3 December 2015). East of the San Andreas Fault (near the Phleger Estate), marine sandstone and mudstone of the Whiskey Hill Formation (**Tw**) overlie Franciscan rocks and reflect bathyal turbidity currents and submarine slumps (Beaulieu 1970; Pampeyan 1993).

Neogene rocks tend to be fine grained and poorly

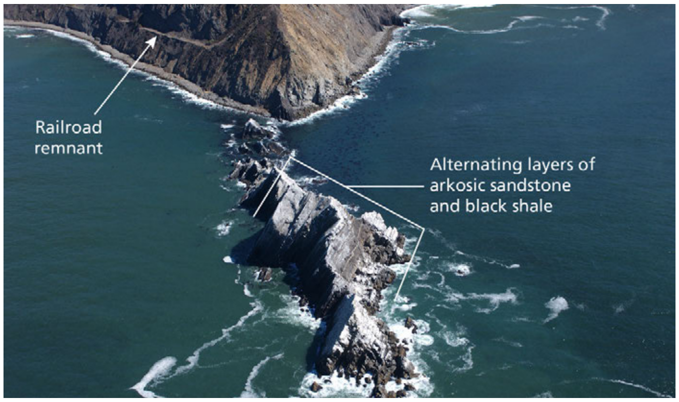


Figure 22. Photograph of Cenozoic turbidite rocks at Point San Pedro. The oldest Cenozoic rocks are two Paleocene turbidite deposits (Tsu, Tsl). Alternating arkosic sandstone and black shale layers comprise San Pedro Rock just offshore from Point San Pedro. Note the cut along the cliff face in the background just above the coastline; this is a remnant of the never completed Ocean Shore Railroad. Photograph copyright © 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org, taken 21 September 2004, used with permission.

Figure 23. Photograph of Fort Funston. From bottom to top, the strata are beach sand (Qbs) covering an active wave-cut platform; the Merced Formation (QTm) exposed in cross section as cliffs; dune sand-younger (Qdsy) deposited on a marine terrace, which is evidence of ancient coastline. In the Merced Formation at Fort Funston, fossiliferous marine deposits alternate with beach, dune, and shore deposits. These relationships suggest that the Merced Formation preserves evidence of at least nine glacial cycles spanning the past 600,000 years (Stoffer 2002). Photograph copyright © 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org, taken 25 September 2010, used with permission.

cemented and are also only mapped west of the San Andreas Fault (Elder 2013). In the park, they include the Purisima Formation (**Tps**), which is part of a continuous marine mudstone and sandstone sequence (also includes **Tm**, **Tsm**, **Tsc** which are not mapped in the park). During the Miocene Epoch, deep basins over the San Francisco Bay block accumulated several kilometers of marine sediments. These extremely thick deposits have potential for oil and gas production (Elder 2013; Stanley et al. 2002). By the late Pliocene Epoch, uplift resulted in the deposition of terrestrial sediments of the Santa Clara Formation (**QTsc**) in the Santa Clara Valley; these deposits are evidence of the development of the modern San Francisco Bay watershed (Vanderhurst et al. 1982; Graham et al. 1984). At the same time—both the Santa Clara and Merced formations contain the 575,000-year-old Rockland ash bed (Sarna-Wojcicki et al. 1985; Lanphere et al. 2004)—but nearer the coast, marine and marginal marine sedimentation is represented by the Merced Formation (**QTm**; Elder 2013). The Merced Formation marks the first post-Miocene marine deposits preserved on the San Francisco Bay block. It likely reflects deposition in a space that opened up behind a northwardly migrating right bend in the San Andreas Fault (Will Elder, Golden Gate National Recreation Area, park ranger, written communication, 30 October 2015). It contains alternating shallow-marine deposits with terrestrial beach dune and shore deposits (Galloway, 1977; Stoffer 2002).Today, the Merced Formation forms the cliffs at Bolinas and Fort Funston (fig. 23).

Formally named Quaternary units mapped in the park include the Colma (**Qc**), Millerton (**Qml**), and Olema Creek (**Qoc**) formations. The Colma Formation consists primarily of shallow-marine sand. Today, the unit forms bluffs along Baker Beach, Land's End, and Ocean Beach. The Millerton and Olema Creek formations are contemporaneous alluvial and estuarine sediments deposited in the San Andreas Fault system north of the Golden Gate.

Surficial Deposits

The youngest map units in the GRI GIS data were deposited during the Pleistocene and Holocene epochs. They are widely distributed throughout the park and were commonly modified or obscured by development, which is sometimes mapped as artificial fill (**Qar**; Pampeyan 1994). Each of these Quaternary ("**Q**") units is associated with ongoing processes, and in some cases more than one process (see "Landslide Deposits and Slope Movements," "Alluvium and Fluvial Processes," and "Coastal Features and Processes" sections).

Folds

Folds are curves or bends in originally flat structures, such as rock strata, bedding planes, or foliation. The two primary types of folds are anticlines which are "A-shaped" (convex) and synclines which are "U-shaped" (concave). As bedrock is compressed by tectonic forces, anticlines and synclines form adjacent to each other. Both types of folds can be overturned—tilted past vertical—by continued or future tectonic forces. Folds frequently "plunge" meaning the fold axis tilts.

Eighty-five unnamed fold features are identified in the GRI GIS data. The only folds mapped in the park (though not in NPS-managed areas) are near Point San Pedro and Seal Cove. At Point San Pedro, Paleocene sandstone, shale, and conglomerate (upper part; **Tsu**) are folded into anticlines, synclines, and overturned synclines. Near Seal Cove, a syncline and an anticline are concealed offshore in unmapped rocks. Smaller folds (not in the GRI GIS data) are common at outcrop scale in the park. For example, the tight "chevron" folds of the ribbon chert along Conzelman Road are particularly well known (fig. 10). Folding in the chert is the result of either slumping that occurred before the sediments were fully hardened or during compression when tectonic activity accreted the chert onto the North American continent (Schlocker et al. 1958).

Faults

A fault is a fracture in rock along which rocks have moved. Faults are classified based on motion of rocks on either side of the fault plane as described in figure 24. The San Andreas is the most well-known but not the only fault in the San Francisco Bay Area. Nearly 390 km (240 mi) of faults are mapped within the authorized boundary of the park, more than 80 km (50 mi) of which are within the managed area. The GRI GIS data include nine named faults, four named fault zones, one named rift zone, and many hundreds of unnamed fault segments. Five of the named faults are mapped within the park's authorized boundaries: the San Andreas, Pedro Mountain, Pilarcitos, Seal Cove, and San Mateo (fig. 25). The structural break resulting from the rotation of the Marin Headlands terrane (see "Franciscan Terranes") suggests a major fault under the Golden Gate (Wakabayashi 1999a).

The GRI GIS data contains 855 unnamed fault segments mapped within the park. As shown in figure 26, these unnamed faults typically surround large blocks of Franciscan rocks among mélange such as at Muir Woods National Monument where a large fault-bounded block of **KJfbch** is mapped at the easternmost extent of the monument. Sheared and brecciated rocks along many of the contacts between units are an indication that the contact is actually a fault.

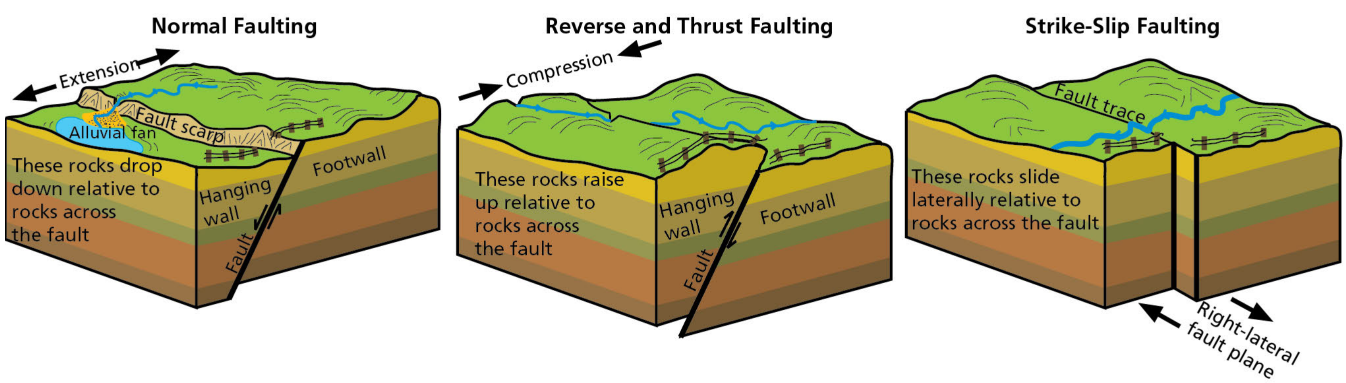


Figure 24. Illustrations of fault types. Movement occurs along a fault plane. Footwalls are below the fault plane and hanging walls are above. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging wall up relative to the footwall. A thrust fault is similar to a reverse fault, but has a dip angle of less than 45°. In a strike-slip fault, the relative direction of movement of the opposing plate is lateral. When movement across the fault is to the right, it is a right-lateral (dextral) fault, as illustrated above. When movement is to the left, it is a left-lateral (sinistral) fault. A strike-slip fault between two plate boundaries is called a transform fault. The San Andreas Fault system is transform with right-lateral movement as illustrated here. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Figure 25. Map of faults south of the Golden Gate Strait. Four named faults, the San Andreas, Pedro Mountain, Pilarcitos, and San Mateo faults, are mapped within the managed boundary of the park along with 855 unnamed fault segments. Only the San Andreas Fault and unnamed faults are mapped north of the Golden Gate Strait. Faults were drawn using the GRI GIS data. Background image and annotations by Esri, DeLorme, USGS, NPS, and NOAA.

Figure 26. Geologic map of Muir Woods National Monument. Mélange (KJfm) underlies nearly all of the national monument. A fault bounded (dashed lines) block of Franciscan Complex chert and metachert (KJfbch) is mapped in a small area of the easternmost part of the monument. Triangles indicate the location of mélange blocks as mapped in the "Mélange Blocks" layer. Alluvium (stream deposits) is mapped as Qalo along Redwood Creek where the creek flows out of the monument. Map by Jason Kenworthy (NPS Geologic Resources Division) using GRI GIS data. Basemap is ESRI "World Topographic Map" layer (accessed 1 July 2016).

The GRI GIS data contain information about several other fault-related features. Clusters of small-scale faults or shear zones are mapped in the Marin Headlands adjacent to the Golden Gate Bridge, in the Presidio, and at Land's End (see the "Geologic Observation Localities" layer in the GRI GIS data). Several northwest trending lineaments (see the "Geologic Line Features" layer in GRI GIS data) are mapped in Rancho Corral de Tierra. A lineament is a landscape-scale linear feature that is a surface expression of an underlying geological structure such as a fault. The lineaments in Corral de Tierra are most likely controlled by faulting (Pampeyan 1994).

The three primary types of faults are normal faults, reverse faults, and transform faults. Thrust faults are reverse faults with a low angle (<45°) fault plane. All three types are represented in GRI GIS data. The transform faults create the significant seismic hazard and risk in the San Francisco Bay Area (see "Geologic Resources Management Issues" chapter). The thrust, reverse, and normal faults create zones of weakness that could be locations for landslides or other slope movements (see "Slope Movement Hazards and Risks" section).

Many of the faults in the park have recognized Quaternary displacement and are considered "active." An active fault is a fault on which slip has occurred recently and is likely to occur in the future. The California Geological Survey updated the Fault Activity Map of California in 2010. The map and accompanying explanatory text list the time period when each fault was last active and references to other works. The map and explanatory text are available at http://www.conservation.ca.gov/cgs/cgs_history/Pages/2010_faultmap.aspx.

Displacement along an active fault may occur suddenly, producing an earthquake (see "Earthquakes" section), or slowly in the form of aseismic (lacking vibrations) creep. Fault creep is the slow rupture of Earth's crust. Active faults in the area exhibit one or the other or both types of movement. For example, the Hayward Fault ruptured suddenly in the 1868 earthquake, but it also exhibits slow surface creep where it crosses highly developed areas in Contra Costa and Alameda counties offsetting and deforming curbs, streets, buildings, and other structures (Bryant and Hart 2007).

Normal Faults

Normal faults form in extensional settings where rocks (or continents) are being pulled apart. That process is sometimes called "rifting" and down-dropped areas surrounded by normal faults may be called "rift zones." Rocks above the fault plane are down-dropped (move down) relative to rocks below the fault plane (fig. 24). In the GRI GIS data, normal faults are mapped along portions of the San Andreas Fault near Upper Crystal Springs Reservoir and along the San Andreas Rift Zone north of the Golden Gate. The Belmont Hill Fault is a normal fault parallel to the San Andreas Fault but mapped outside the park near Belmont. A few, very short, normal fault segments are mapped in the Marin Headlands.

Reverse and Thrust Faults

Reverse and thrust faults form in compressional settings where rocks (or tectonic plates) are being pushed together. Rocks above the fault plane were uplifted (moved up) relative to rocks below the fault plane (fig. 24). A thrust fault is a type of reverse fault that has a low fault plane angle. An unnamed reverse fault is mapped outside the park west of Upper Crystal Springs Reservoir. Thrust faults are abundant in the Marin Headlands where they formed tens of millions of years ago during terrane accretion when the plate boundary was a subduction zone (Sloan 2006). An excellent example of internal thrust faults occurs in the Marin Headlands, where the stratigraphic sequence (basalt, chert, and graywacke) is wholly or partially repeated at least 11 times (Wahrhaftig 1984). Also, a long, continuous thrust fault along the Webb Creek Valley between Mount Tamalpais and the Pacific Ocean forms the contact between an area primarily mapped as mélange (**KJfm**) in the south and Franciscan rocks to the north.

The Serra fault is another documented thrust fault (see Hall 2001 and Kennedy 2005), though it is not identified in the GRI GIS data as such. It is the northernmost thrust fault in the northwest-striking Serra fault zone, which is roughly parallel to and a mile or two northeast of the San Francisco Peninsula segment of the San Andreas Fault (just outside the boundary of the park). Movement along the fault thrust older Franciscan rocks and the Merced Formation (on the west side of the plane) up and over younger Colma Formation deposits (to the east of the fault plane). A buried northern arm of the Serra fault (not in the GRI GIS data) intersects the cliffs at Fort Funston where the uplifted Merced Formation is visible as a marine terrace above the younger Colma Formation (Kennedy 2005; Hall 2001; see "Coastal Features and Processes" and "Uplift" sections of the "Geologic History" chapter).

As the Serra fault plane extends deep underground, it tilts and eventually ties in with the San Andreas Fault (Hall 2001). Many of the northwest-striking range-front thrust faults, including the Serra Fault, dip southwest towards the San Andreas Fault and probably merge with it at depth (Kennedy 2005). However, no evidence links the Serra fault to any recent ground motion. The Serra Fault did not move significantly during either the 1906 San Francisco or 1989 Loma Prieta earthquakes. Nevertheless, the Serra intersects the San Andreas and the two faults are considered seismically related systems such that earthquakes along the San Andreas may trigger movement along the Serra (Hall 2001). Whether the Serra Fault ever generated any motion independently of the San Andreas Fault is unclear (Hall 2001).

Transform Faults

Transform faults occur where rocks (or tectonic plates) move past each other ("strike-slip") along the fault plane with relatively little motion up or down ("dip-slip") on the fault plane. Although most of the faults mapped in the GRI GIS data are denoted as "unknown offset/displacement," with the exception of the Belmont Hill Fault, the San Andreas and all the other named faults in the GRI GIS data are primarily right-lateral strike-slip faults. The term "right-lateral" or "dextral" indicates that relative motion along the fault is "to the right." In other words, to a person looking across the fault, the other side has moved to their right (fig. 24).

Transform faults accommodate seafloor spreading and are typically found along mid-ocean ridges. From afar, seafloor spreading centers, such as the East Pacific Rise, appear as long linear ridges crossing the ocean floor. Upon closer inspection, transform faults break the ridges into smaller sections. Those faults "transform" plate movement from one spreading-center segment to another. The San Andreas Fault system is essentially

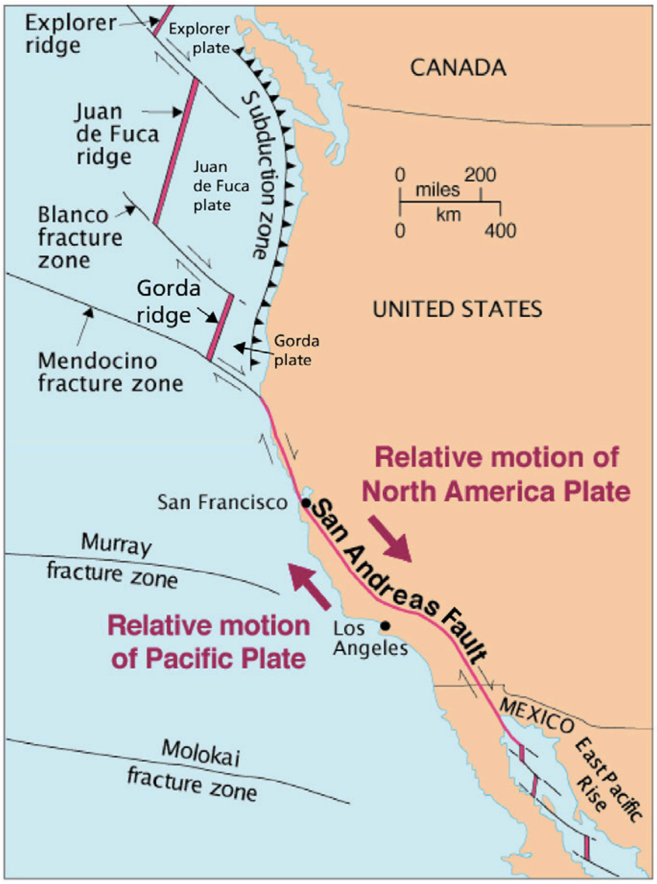


Figure 27. Plate tectonic map of western North America. The San Andreas Fault alone does not constitute the boundary between the North American and Pacific tectonic plates. This graphic shows all of the features which combined tectonically separate the North American plate from the Pacific plate. The Farallon plate, though mostly subducted, is still represented by relatively small, still-subducting remnants (Explorer, Juan de Fuca, and Gorda plates). The fragments are separated by a series of offshore transform faults (Blanco, Mendocino, Murray, and Molokai fracture zones) and isolated segments of the East Pacific Rise (Explorer, Juan de Fuca, and Gorda ridges). US Geological Survey graphic by Kious and Tilling (1996, figure 25) with additional annotations by the author.

one of these transform faults that has intersected continental crust and elongated substantially. It transforms spreading movement from the East Pacific Rise in the Gulf of California to the Juan de Fuca Ridge off the coast of Oregon (fig 27).

San Andreas Fault System

It is hard to imagine any region of the country where faults are more interwoven into public awareness than in California. And it is hard to imagine any geologic feature in the park, or perhaps the entire west coast of the United States, more well-known than the San Andreas Fault. The San Andreas Fault is a definitive geologic—and popular culture—feature of the Bay Area and the state of California.

The San Andreas Fault system is a network of large, northwest-trending, right-lateral transform faults that cut across south and central California. In the San Francisco Bay Area, the western branch of the system runs along the coast, nearest to the park, and consists of the Pilarcitos, San Gregorio, and San Andreas faults (fig. 25). The East Bay branch of the system includes the Hayward, Calaveras, Rodgers Creek, and Greenville faults (fig. 25). Knowledge of fault location and activity is continuously changing as more research is completed (Will Elder, Golden Gate National Recreation Area, park ranger, conference call, 6 May 2014). For example, a strand of the San Gregorio Fault shows evidence of activity (conference call participants, 6 May 2014).

The San Andreas Fault system is globally significant because it is an "exceptional example" of a plate margin visible and accessible on land whereas many other plate margins are at the bottom of the oceans (Wallace 1990). The roughly 1,350-km- (840-mi-) long fault system represents a transform boundary between the Pacific plate to the west and the North American plate to the east (fig. 27). In the San Francisco Bay Area, Monterey, Santa Cruz, Pacifica, and the Point Reyes Peninsula are on the Pacific plate, whereas San Jose, San Francisco, and San Rafael are on the North American plate.

The San Andreas Fault system is one of the most active transform faults on the planet (Hirth and Guillot 2013). Spatial distribution of large earthquakes over the past 200 years defines the San Andreas Fault system as a 100- to 300-km- (60- to 200-mi-) wide zone containing numerous active faults in addition to the San Andreas Fault (Ellsworth 1990). The system creates significant seismic hazards and risk (see "Geologic Resource Management Issues" chapter) for more than half of the 38.8 million residents of California including the 7.4 million people in San Francisco Bay Area (second most densely populated major city in the country) and 12.8 million people in the Los Angeles Metropolitan Area (second largest metro area in the country).

On a global scale, the San Andreas Fault system is part of a more complex system of tectonic plate interactions that will ultimately culminate in the complete subduction of the now-fragmented, eastward-moving Farallon plate—a massive oceanic plate that was between the Pacific and North American plates hundreds of millions of years ago. The system now includes other transform faults (Blanco, Mendocino, Murray, and Molokai fracture zones), isolated segments of the East Pacific Rise mid-oceanic ridge (Explorer, Juan de Fuca, and Gorda ridges), and relatively small, still-subducting remnants of the Farallon plate (Explorer, Juan de Fuca, and Gorda plates; fig. 27; Wallace 1990). Today, these combined features tectonically separate the North American plate from the Pacific plate (Wallace 1990).

The San Andreas Fault came into existence roughly 28 million years ago in what is now Southern and Baja California at a point called the Mendocino triple junction—the location where the Farallon, Pacific, and North American plates intersect. This is where the East Pacific Rise first encountered the Farallon subduction zone. As the plates continued to move, the Mendocino triple junction migrated northward, and the San Andreas Fault developed behind it and lengthened as it moved. The San Andreas Fault reached the San Francisco Bay Area around 15 million years ago (Atwater 1970, 1989; Page and Wahrhaftig 1989; see "Geologic History" chapter).

As the San Andreas Fault system reached the Bay Area, the local bedrock became broken among the various faults which compose the system. The areas between individual faults are known as fault blocks; each block has a distinct basement and history of movements and rotations (see Jachens et al. 2002 for description of blocks). Movement among the blocks occurred from 15 million years ago to about 7 million–5 million years ago and had a major effect on Cenozoic deposition (see "Cenozoic Rocks" section; Elder 2013).

Throughout most of central California, the San Andreas Fault is bounded by the Franciscan Complex to the east (see various sections describing Franciscan rocks and terranes in this chapter) and granitic rocks of the Salinian complex (block) to the west (see "Salinian Complex" section in this chapter; Irwin 1990; Clark and Brabb 1997; Anderson et al. 2001). One exception occurs on the Pilarcitos fault block—a block west of the San Andreas Fault which contains Milagra Ridge, Mori Point, and Sweeney Ridge. Here, seemingly out of place, Franciscan rocks appear west of the San Andreas Fault. The Pilarcitos fault block may be a former piece of the North American plate that has been captured by the Pacific plate (McLaughlin et al. 1996) or the Pilarcitos Fault may be an old thrust fault unrelated to the San Andreas (Wakabayashi 1999a)

Geologists commonly use the analogy that the Pacific plate is moving north at about the rate that fingernails grow, which is approximately 4.2 cm (1.7 in) per year (Yaemsiri et al. 2010). Over long periods of time, this seemingly small amount of displacement translates to immense amounts of offset. One of the most exceptional examples is the correlation of the Neenach and Pinnacles volcanic rocks which are derived from the same ancient batholith but exposed today on opposite sides of the fault some 315 km (195 mi) apart (Matthews 1976; Irwin 1990; Stoffer 2002). Irwin (1990) calculated an annual displacement rate along the San Andreas Fault of just 1.4 cm (0.55 in) per year based on these rocks. More recent displacement is apparent locally in the Santa Clara (**QTsc**) and Merced (**QTm**) (see poster in pocket).

Since the 1970s geologists have noted a discrepancy between the rate of displacement across the San Andreas Fault—1.4 cm (0.55 in) per year (Irwin 1990)—and that across the entire plate boundary—about 3.9 cm (1.5 in) per year based on modern geodetic data (Argus and Gordon 2001; Field et al. 2015). Because movement along the San Andreas Fault cannot account for the entire displacement along the plate boundary, part of the total movement must occur in small increments along other faults in a broad zone that may extend from the continental boundary all the way to the Basin and Range province east of the Sierra Nevada (Irwin 1990).

Not all of the motion along the San Andreas Fault system is transform, many of the faults in the system display some component of vertical motion, both up (compression) and down (extension). Where a right-lateral transform fault bends to the left, compression and uplift, often involving thrust faults, occurs (fig. 2). The actively uplifting Santa Cruz Mountains where the San Andreas Fault bends left is an example of this (Elder 2013). Where a right-lateral transform fault bends right, extension and down-dropped areas form valleys (Sloan 2006). Today, about 90% of the movement is transform and 10% is vertical motion (Sloan 2006). The vertical component is squeezing together the Pacific and North American plates and causing the land to fold, fault, and rise. The characteristic hills of the San Francisco Bay Area are related to this thrust faulting along offsets or bends in faults (Sloan 2006). For example, Mount Diablo and the East Bay Hills are rising about 1–2 mm (roughly 1/16 in) per year (Sloan 2006). Mount Tamalpais is moving up along the thrust fault mapped in the Webb Creek Valley (Sloan 2006). Movement along the Serra thrust fault of the San Andreas Fault system is raising the Merced Formation and exposing it to coastal erosion at Fort Funston (see "Thrust and Reverse Faults" section; Stoffer 2002).

Most of the faults of the San Andreas system are considered active. Movement causes both rapid seismic shaking (earthquakes; described in the next section) and aseismic creep (without shaking). The segments of the San Andreas Fault in the vicinity of the park have historically experienced earthquakes rather than creep. While to the south of the park, near San Juan Bautista, the fault creeps at a rate of 3.2 cm (1.25 in) per year (Sloan 2006). Segments on which gradual fault creep has occurred are less likely to produce strong earthquakes (Wallace 1990). "Locked" segments of the faults—those that do not experience creep—are capable of producing large, but uncommon, earthquakes. Many of the faults in the San Andreas Fault system are seismically connected, meaning that an earthquake along one could generate movement on another.

Some geologists have suggested that the San Andreas Fault creeps through segments high in serpentinite, which is a relatively "slippery" (lower friction) rock (see "Serpentinite" section). However, the Hayward Fault creeps in areas without identified serpentinite, thus serpentinite is not the only factor contributing to creep (Sloan 2006). Another proposal is that carbon-dioxide rich springs in Franciscan rocks may increase "pore pressure" and thereby reduce friction, potentially causing aseismic creep (e.g., Irwin and Barnes 1980). Areas of reduced friction would be more likely to creep because they cannot "store" the large amounts of energy needed to create a massive earthquake.

Earthquakes

Earthquakes are ground vibrations—shaking—that occur when rocks under stress suddenly move, abruptly releasing slowly accumulated energy (Braile 2009). Earthquakes are almost always generated along preexisting faults because faults are zones of weakness. The "epicenter" of an earthquake is the point on the Earth's surface directly above the "focus" of the earthquake, which is the point in the crust where movement along the fault began. Refer to http://earthquake.usgs.gov/learn/glossary/ for nontechnical definitions of earthquake terminology.

The "size" or "strength" of an earthquake can be measured by its magnitude and its intensity. An earthquake's magnitude is a measure of the energy released. The "Richter magnitude" is a well-known scale that measures the amplitude (size) of the waves recorded by seismographs. The Richter magnitude is a logarithmic scale meaning that for each whole number increase in magnitude, a ten-fold increase in amplitude occurs and a 31-fold increase in energy is released. For example a 6.0 earthquake has wave amplitudes 10 times the size of a magnitude 5.0 (100 times the size of a 4.0) and releases 31 times the energy of a 5.0 earthquake (961 times the energy of a 4.0). By comparison, earthquake intensity is a relative scale, using Roman numerals, to describe how an earthquake affects the Earth's surface, human perception, and structures. The Modified Mercalli scale is commonly used in the United States. Intensity values range from imperceptible by humans (I) to total destruction of developed areas and alteration of the landscape (XII). Notably, although every earthquake has just one magnitude, intensities vary based on local geology, proximity to the epicenter, and construction style of local structures. The US Geological Survey calculates and reports the magnitude of earthquakes. "ShakeMaps" show the different intensities experienced for a given earthquake throughout the region. The maps are available at http://earthquake.usgs.gov/earthquakes/shakemap/.

Tens of thousands of earthquakes occur in California every year and on the active faults in the park every day, but only a few are large enough to be felt (Sloan 2006). Four historic earthquakes have caused considerable damage—measured in damage to property and loss of life—in the San Francisco Bay Area: (1) the 1868 Hayward fault earthquake (estimated magnitude 7), (2) the 1906 San Francisco earthquake (estimated magnitude 7.9), (3) the 1989 Loma Prieta earthquake (estimated magnitude 7), and (4) the 2014 South Napa earthquake (estimated magnitude 6) (US Geological Survey 2012).

One of the most spectacular effects of large earthquakes is surface fault rupture (US Geological Survey 2006). Surface rupture occurs when movement on a fault deep within the Earth breaks through to the surface (fig. 28). Not all earthquakes result in surface rupture. Surface rupture commonly produces a complex pattern of fractures, which are often described using the terms fault branch, splay, or strand (Wallace 1990). Only three earthquakes in the region have documented surface rupture: (1) the 1980 Livermore on the Greenville and Las Positas faults, (2) the 1868 on the Hayward Fault, and (3) the 1906 San Francisco earthquake on the San Andreas Fault (US Geological Survey 2006). The Loma Prieta earthquake of 1989 caused major damage in the San Francisco Bay Area but the movement deep in the Earth did not break through to the surface.

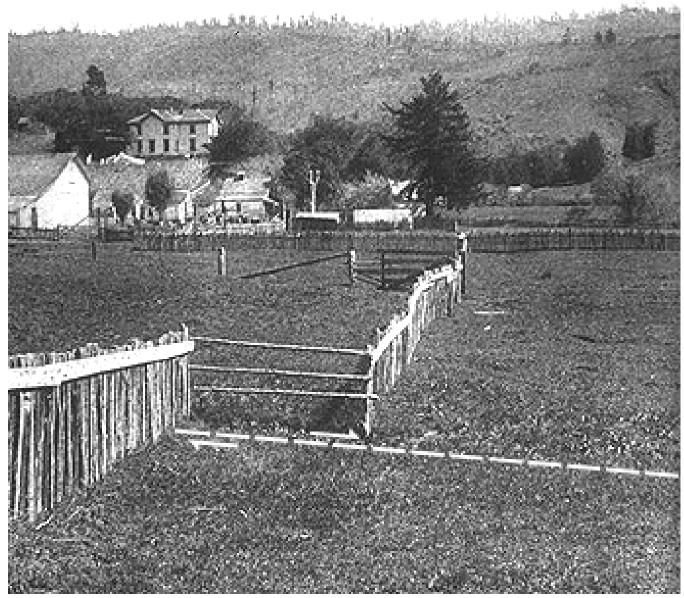


Figure 28. Photograph of a fault-offset fence. A fence near Bolinas was offset about 3 m (10 ft) by surface rupture during the 1906 San Francisco earthquake. Dashed line shows the fault and arrows show direction of relative motion. US Geological Survey photograph, available at http://geomaps.wr.usgs.gov/sfgeo/quaternary/stories/marin_rupture.html.

The 1906 San Francisco earthquake had a maximum intensity of XI ("extreme") in San Francisco. The earthquake and resulting fire killed more than 3,000 people and destroyed more than three-quarters of the city. It was one of the most costly natural disasters in the history of the United States and the most deadly in California's history. The San Andreas Fault ruptured along approximately 477 km (296 mi) of its length, from San Juan Bautista, directly through the park, to the Mendocino triple junction at Shelter Cove (south of Eureka) (Ellsworth 1990; US Geological Survey 2012). The amount of displacement varied markedly along the affected stretch, ranging from as little as 1.5 m (5 ft) up to 8.5 m (28 ft) near Olema between the park and Point Reyes National Seashore (Ellsworth 1990; Irwin 1990; Sloan 2006; US Geological Survey 2006). It was felt as far away as Oregon and central Nevada and strong shaking was experienced as far north as Eureka and as far south as King City. The Ocean Shore Railroad, which was intended to connect San Francisco and Santa Cruz via a route along the coastline, sustained significant damage during the earthquake and ultimately never recovered. Remnants of the railway are visible along the cliff face at Point San Pedro (fig. 22).

Though tragic, the 1906 San Francisco earthquake ultimately led to groundbreaking revelations in the scientific understanding of earthquakes. In the wake of the incident, then California Governor Pardee commissioned a scientific investigation which resulted in the production of an exhaustive compilation of detailed reports from more than 20 contributing scientists; this monumental work (Lawson 1908) is now commonly referred to as "the Lawson report." The key findings of the report were the correlation between earthquake intensity/damage and geologic conditions, and the presentation of the "theory of elastic rebound" by H. F. Reid (1910). The Lawson report showed that damage to buildings was strongly related to geology; that is, damage was greatest on artificially filled ground and incoherent sand, and least on top of bedrock. The elastic rebound theory was the first theory to satisfactorily explain the mechanism of earthquake production. The Lawson report remains the authoritative work on earthquakes to this day.

The 1989 Loma Prieta earthquake had an estimated magnitude of 7.1 with 2 m (6 ft) of horizontal displacement and no surface rupture (Ellsworth 1990;

Sloan 2006). Maximum intensity in San Francisco was IX ("severe"). The San Andreas Fault re-ruptured a length of about 40 km (25 mi) along the 1906 fault break (Ellsworth 1990; USGS 2006). The greatest amount of damage and loss of life occurred where earthquake-induced liquefaction occurred in San Francisco and Oakland, about 100 km (60 mi) northwest of the earthquake epicenter. The condition of both the ground and structures played a major role in the destruction incurred in these locations relative to areas closer to the epicenter (see "Earthquake Hazards and Risks" section).

The most recent earthquake to cause considerable damage in the San Francisco Bay Area was a magnitude 6.0 earthquake referred to as the "South Napa earthquake." It occurred on Sunday 24 August 2014 at approximately 3:20 a.m. According to the US Geological Survey, the epicenter was just north of the Bay Area, near Sonoma Valley and Napa Valley and American Canyon. Fault rupture occurred at a depth of 11 km (7 mi). Shaking in the park was only light (intensity IV) to moderate (V). Maximum intensity was "severe" (VIII) closer to the epicenter. The earthquake caused more than $300 million in damages.

Geothermal Systems and Hydrothermal Features

Geothermal systems transfer heat from within the Earth toward its surface (Heasler et al. 2009). When the transfer of heat involves water, hydrothermal features representing the geothermal system may form on Earth's surface (Heasler et al. 2009). Examples of hydrothermal features include hot springs, geysers, mud pots, and fumaroles such as those at Yellowstone National Park. A "hot spring" is a spring that has a temperature greater than the human body (37°C [98°F]) (Stoffer 2002).

Sixteen geothermal systems managed by the National Park Service are designated as "significant" by the Geothermal Steam Act of 1970, as amended in 1988 (see Appendix B) and require monitoring. None of these are in Golden Gate National Recreation Area, Fort Point National Historic Site, or Muir Woods National Monument. The NPS Geologic Resources Division Geothermal Systems Monitoring website, http://go.nps.gov/monitor_geothermal, provides additional information. See also the "Geothermal Resource Protection" section.

One hot spring occurs in the authorized boundaries of the park; it is just outside the NPS-managed area along the coast near Steep Ravine Beach (Daphne Hatch, Golden Gate Natural Recreation Area, chief of natural resources, conference call, 6 May 2014). The spring appears to be mapped in Franciscan mélange (**KJfm**), with an area of serpentinite (**KJfsu**) nearby. This hot spring goes by several informal names including Steep Ravine hot spring, Marin tidal hot spring, and Rocky Point hot spring. Spring water discharges through a cave into a pool. The pool is only exposed at low tide and is only accessible by foot down a steep and somewhat treacherous path. Nevertheless, it is a popular destination for bathers, and visitors could be altering the natural condition of the spring. Geothermal "vents" may be present near the base of the cliffs and visitors might be digging into the beach and cliff base to access warm water.

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; examples include 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 July 2016, 262 parks, including Golden Gate National Recreation Area, had documented paleontological resources in at least one of these contexts. The NPS Fossils and Paleontology website, https://www.nps.gov/subjects/fossils/index.htm, provides more information.

The park contains considerable paleontological resources, from Cenozoic Era mammal material to Mesozoic Era marine invertebrates in Franciscan terranes; the potential exists for continued discovery (Elder et al. 2008). A paleontological resource inventory for the park was completed by Henkel et al. (2015). It detailed the scope, significance, and resource management considerations for fossils within the park. Fossils within the Cenozoic rocks have been well known to professional and amateur paleontologists for many years (Henkel et al. 2015). Fossils in the Franciscan rocks provided important evidence of the rocks ages, as well as their original depositional environment and location. That information was critical to reconstructing the paleogeographic history of the terranes and the timing of their accretion to North America.

Resource management issues associated with fossils in the park are discussed in the "Paleontological Resource Inventory, Monitoring, and Protection" section and detailed by Henkel et al. (2015).

Eroding sea cliffs and active faulting are likely to unearth additional fossils (Henkel et al. 2015). Many fossils remain in situ (in their natural location), while others are housed in the park's collection, the University of California Museum of Paleontology (UCMP), and the California Academy of Sciences (CAS). Information about the park's fossil collection is stored at UCMP and can be found by searching that museum's catalog at http://ucmpdb.berkeley.edu/loc.html. Lands within the authorized boundary of the park have produced six holotype specimens (four from Cenozoic rocks and two from Franciscan rocks) (Henkel et al. 2015). A holotype is the single, original specimen upon which a species is scientifically named and described.

Fossils From Cenozoic Rocks

Cenozoic rocks in the park contain fossil invertebrates, vertebrates, plants, trace fossils, and microfossils (pollen and diatoms) (Elder et al. 2008; Henkel et al. 2015). Of the Cenozoic geologic units mapped in the park, the Pliocene–Pleistocene Merced Formation (**QTm**) is the most fossiliferous; it has yielded the remains of land mammals (bison, camels, mammoths, mastodons, horses, and ground sloths), marine mammals and birds, terrestrial and marine trace fossils, plant fossils, and marine invertebrates (mollusks and echinoderms) (Henkel et al. 2015). In addition, the Colma formation (**Qc**) in the park has mammoth fossils (Henkel et al. 2015), and the Millerton Formation (**Qml**) contains abundant fossil fauna and flora (Clark and Brabb 1997).

Four species were originally named and described from holotype specimens collected from Cenozoic rocks and deposits within the park (Henkel et al. 2015). The gastropods (snails) *Nucella megastoma* (Vermeij and Powell 2004) and *Campanile greenellum* (Hanna and Hertlein 1939) were named from specimens collected at Seven Mile Beach (CAS 69251; map unit **QTm**) and near Devil's Slide (CAS 7233; map units **Tsl** and **Tsu**), respectively (Henkel et al. 2015). The bivalve (clam) *Spisula mossbeachensis* (Glen 1959) was named from a specimen (UCMP 37643) collected from the Purisima Formation (**Tps**) of Moss Beach (Henkel et al. 2015). Finally, Andrew Lawson collected a pinecone (UCMP 20533; map unit **QTm**) that was subsequently described by Axelrod (1967) as *Pinus lawsoniana* from near Mussel Rock (Henkel et al. 2015).

Fossils From Franciscan Rocks

Both microfossils and macrofossils (fossils that can be observed with the unaided eye) have been documented in Franciscan rocks within the park's authorized boundaries. The sources of the fossils are mélange (**KJfm**) and the Permanente, Alcatraz, and Marin Headlands terranes of the Franciscan Complex (Henkel et al. 2015). Microfossils are abundant in some Franciscan chert and limestone while macrofossils are rarely discovered in Franciscan rocks. Microfossils include radiolarian tests, which make up the bulk of the bedded chert deposits (**KJfc**, **KJfbch**) in the park, and foraminifera, which are common constituents in limestone blocks of the Permanente terrane (**Kfl**, **KJfl**). The macrofossils are marine mollusks (e.g., clams and snails).

Although macrofossils are rare in Franciscan terranes, a variety of mollusks have been discovered on Alcatraz Island, in the Marin Headlands terrane and in Franciscan mélange ("Central terrane"). Four bivalves (clams) and one gastropod (snail) are reported from the Alcatraz terrane on Alcatraz Island. Two of the bivalve species were new species and named from holotypes collected on Alcatraz Island, *Lucina alcatrazis* (Anderson 1938; UCMP 10026) and *Inoceramus elliotii* (Gabb 1869). *I. elliotii* was the first fossil discovered in the park; it was found in a load of rock that was removed from Alcatraz Island (Bailey et al. 1964; Blake et al. 2000). The two other bivalve fossils (*Buchia pacifica* and *Pleuromya* sp.) were reported by Armstrong and Gallagher (1977), but those fossils have been lost (Henkel et al. 2015). Recently, a high-spired gastropod was found on the island (Henkel et al. 2015). Two ammonites, one gastropod, and one belemnite are reported from the Marin Headlands terrane. Graywacke yielded the two Cretaceous ammonite fossils, *Mantelliceras* sp. (Matsumoto 1959) and *Douvilleiceras* cf. *D. mammillatum* (Elder 1998, 2001; Henkel et al. 2015). A gastropod, *Paladmete* cf. *P. perforata* (Schlocker et al. 1954; Hertlein 1956), and a Jurassic belemnite, *Acroteuthis* sp. (Wright 1974), are also documented from this terrane (Henkel et al. 2015). Sandstone blocks of the Central terrane mélange in the

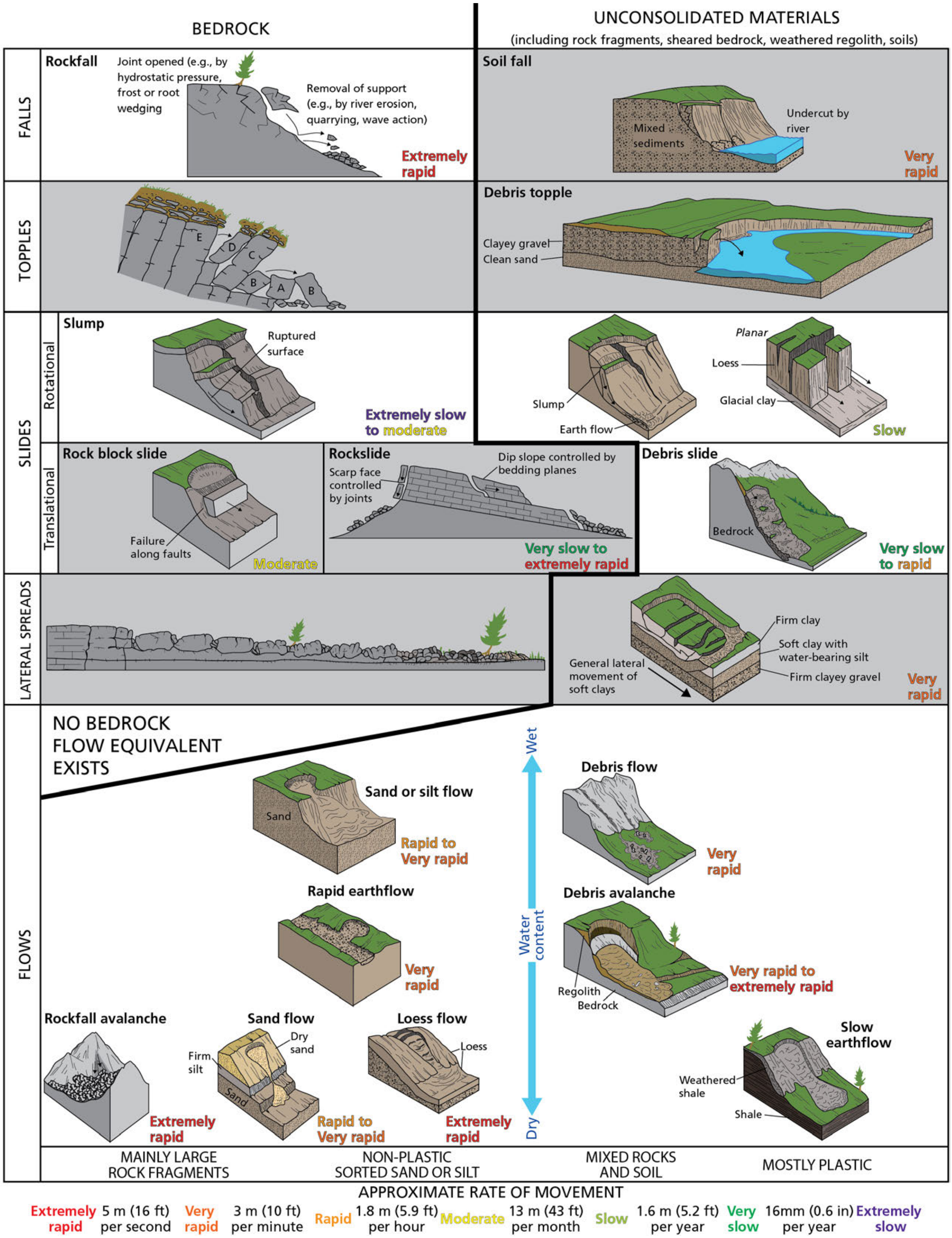


Figure 29. Illustrations of slope movements. Different categories of slope movement are defined by material type, nature of the movement, rate of movement, and moisture content. White boxes indicate types of landslides that are common causes of damage in the park, though other types of slope movements may occur and may also cause damage. Graphic by Trista Thornberry-Ehrlich (Colorado State University) redrafted after a graphic and information in Varnes (1978, figure 4.33) and Cruden and Varnes (1996).

park have yielded two bivalve specimens, a Late Jurassic to Early Cretaceous *Buchia* sp. and an Early Cretaceous *Buchia pacifica* (Bailey et al. 1964; Wahrhaftig and Lehre 1974; Henkel et al. 2105).

Landslide Deposits and Slope Movements

Map units **Qyl**, **Qls**, **Qsr**, **Qcl**, and **Qol**

Slope movements, generally referred to as "landslides," occur frequently in the park. Landslide refers to the downslope movement of soil, regolith, and/or rock under the influence of gravity as well as the resulting deposit (Highland and Bobrowsky 2008). Types of landslides are defined by the material involved (bedrock or unconsolidated material), nature and rate of movement, and moisture content. Slope movements may occur relatively slowly and continuously or they may occur abruptly and rapidly. Four types of landslides are common (though many types may occur) in the San Francisco Bay region: rockfall, slumps, debris slides, and earth/debris flows (San Francisco Bay Landslide Mapping Team 1997; Sloan 2006). Refer to figure 29 for illustrations of slope movements. Slope movements create geologic hazards and associated risk (see "Geologic Resource Management Issues" chapter).

In general, landslides in the park occur on steep slopes and in weak rocks, and are triggered by rainfall or earthquakes (Wills et al. 2011). Nowhere is this more apparent than along coastal cliffs where wave action steepens slopes and may even undercut them, further adding to their instability (Williams 2001). Groundwater seeping out of cliff faces augments the destabilizing action of waves on coastal cliffs (Williams 2001). Bluffs of the Merced Formation at Fort Funston are receding multiple meters (tens of feet) per year due to land loss from slope movement (fig. 23; Daphne Hatch, Golden Gate National Recreation Area, chief of resource management, conference call, 6 May 2014). Other well-known coastal landslide locations include serpentinite

Figure 30. Photograph of the Battery Townsley landslide. Evidence of rockfall, slumps, and debris slides on many scales is common along coastal cliffs in the park. This landslide measures approximately 150 m (500 ft) wide by 530 m (1,700 ft) long (from top scarp to ocean). Photograph copyright © 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org, taken 5 October 2005, used with permission.

Figure 31. Photograph of rockfall along a cliff. Large boulders (see car for scale) are evidence of rockfall, which is likely a regular occurrence though rarely observed (see fig. 32). Photograph copyright © 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org, taken 27 September 2013, used with permission.

slides at the Presidio (fig. 14), the massive Devil's Slide area, Seal Cove, and Battery Townsley near Tennessee Cove (fig. 30). Small coastal slope movements, such as the tumbling of boulders and rocky debris down cliffs (fig. 31) are probably quite common, though rarely witnessed. By chance, on the afternoon of 29 December 2012, the collapse of an arch at Tennessee Beach was caught on camera by a family out for a hike; the entire event took place in under a minute (fig. 32; Chris Wills, California Geological Survey, geologist, email communication, 29 December 2012).

Steep slopes also occur away from the coast. Human activities, such as road cutting, can create steep cliffs susceptible to landslides. Many large slides have taken place along the Pilarcitos and San Mateo creeks where canyons in fault zones have steep, northeast-facing, colluvium-covered walls and relatively high soil moisture (Pampeyan 1994). Numerous shallow debris flows on Montara Mountain, occurring during or following prolonged periods of precipitation, have little economic consequence (Pampeyan 1994). Although, north of San Pedro Valley, shallow debris flows in colluvium triggered by heavy rains in January 1982 caused deaths and significant property damage (Howard et al. 1988; Pampeyan 1994).

Slumps and slides occur on less steep slopes, such as those in the interior of the Marin Headlands, when the conditions (e.g., abundant rainfall; California Governor's Office of Emergency Services 2013) are right. Weak and highly fractured rocks such as serpentinite and mélange form hills where slumps and landslides are common; maps show that most landslides in the park are clustered in Central terrane bedrock areas, which is mélange (Elder 2013). At the time of GRI report preparation, a slide in mélange occurred in the Camino del Canyon area of Muir Woods National Monument (Tamara Williams, Golden Gate National Recreation Area, hydrologist, personal communication, 13 October 2015). Soft and slippery weathered serpentinite may act as a slip surface for slumps. The hummocky ground surface produced by these slope movements has been called "melted ice

Figure 32. Photographs of an arch before and after its collapse. By chance, while on a hike, California Geological Survey geologist, Chris Wills, and his son, observed and documented the collapse of an arch at Tennessee Beach. The event occurred in less than a minute. Photographs taken on 29 December 2012 by Chris Wills (California Geological Survey).

cream topography." Erosion of this nature has been more or less the same over the past 10,000 years in the interior of the Marin Headlands. It, rather than large landslides, accounts for most of the geomorphologic change (O'Farrell et al. 2007).

In the GRI GIS data, landslide deposits are common along the coast, in the interior of the Marin Headlands, and anywhere steep slopes occur (e.g., Montara Mountain, Sweeney Ridge, and Milagra Ridge). In the park, slope and ravine debris (**Qsr**), which accumulated by slow downslope movement, is the most extensively mapped landslide deposit. Older landslide deposits (**Qol**) are likely inactive; younger landslide deposits (**Qyl**, **Qls**) are considered active (Pampeyan 1994). Landslide escarpments (in the "Hazard Feature Lines" layer) mark the location of past landslides. Colluvium (**Qcl**) can be considered, at least in part, a landslide deposit because it accumulates via a combination of slow downhill, gravity-driven creep and surface runoff.

As mapped by Pampeyan (1994), and included in the "Hazard Point Features" layer of the GRI GIS data, 407 "shallow landslides" (<10 ft thick and <100 ft

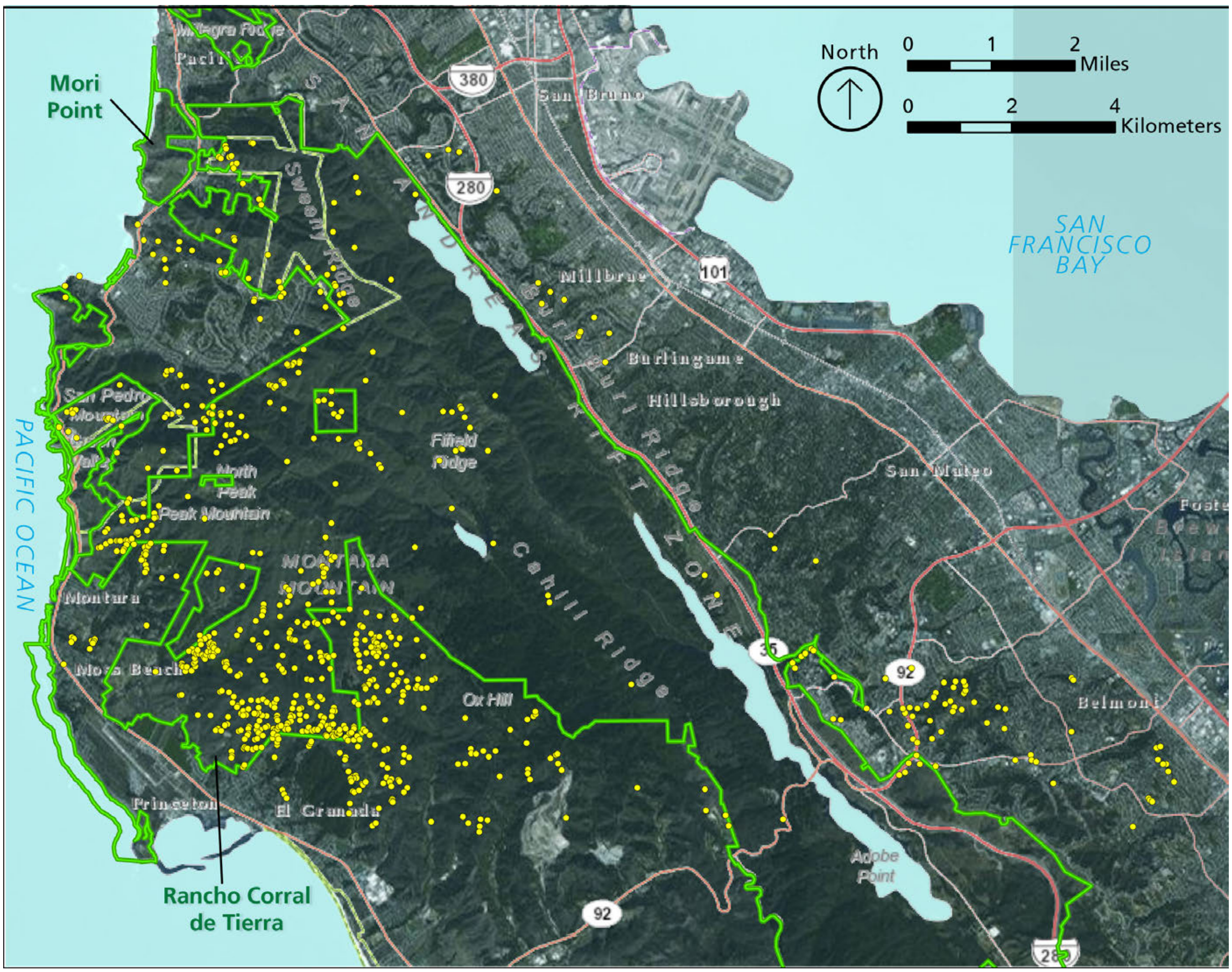


Figure 33. Map of shallow landslides in Golden Gate National Recreation Area. The yellow dots indicate "shallow landslides" (< 3 m [10 ft] thick and < 30 m [100 ft] diameter) that are mapped within the authorized boundaries (green lines) of the park in the "Hazard Point Features" layer of the GRI GIS data. All of these shallow landslides are south of San Francisco, which is a result of the extent of the original source map area (see Pampeyan 1994) and not an indication that shallow landslides are absent in other locations within the park. Map compiled by the author using GRI GIS data. Background aerial image by Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

diameter) are mapped within the authorized boundary of the park. Of these, 279 are mapped in the Corral de Tierra managed area of the park and 18 are mapped at Sweeney Ridge (fig. 33). All of these "shallow landslides" are south of San Francisco, but that is a result of the extent of the original source map area (see Pampeyan 1994) and not an indication that shallow landslides are absent in other locations within the park. Refer to the "Slope Movement Hazards and Risks" section for more information about landslide mapping and assessment.

In addition to active slope movements, ancient slope movements are significant to the geologic story of the park. Slope movements played a major part in the formation of classic Franciscan rocks. Throughout geologic time, large-scale submarine landslides called turbidity flows have slid off the coast of California (see "Graywacke and Shale" section) and settled at the base of the continental slope. The graded bedding of Franciscan graywacke turbidite deposits records these massive underwater slides.

Alluvium and Fluvial Processes

Map units **Qya**, **Qsc**, **Qyf**, **Qyfo**, **Qst**, **Qafy**, **Qaly**, **Qalo**, **Qam**, **Qafo**, **Qcl**, **Qpf**, **Qpaf1**, **Qoal**, **Qof**, **Qpoaf**, **Qtmr**, **Qmst**, **Qoc**, and **Qml**

Fluvial refers to rivers and streams and the landforms and deposits created by them. Alluvium is the material, such as clay, silt, sand, and gravel, deposited by a stream. Alluvium in the park was deposited in both modern and ancient stream beds, floodplains, fans at the base of steep slopes, and on stream terraces.

Fluvial processes are active in the park today; numerous creeks crisscross the park. Most of the Quaternary alluvium is mapped in modern stream valleys or gulches. The location of older alluvial deposits can be used to understand how the San Francisco watershed developed. For example, the Santa Clara Formation (**QTsc**) represents northwest flowing braided stream deposits that probably indicate the beginning of the modern San Francisco watershed during the late Pliocene to early Pleistocene epochs (see "Cenozoic Rocks" section and "Geologic History" chapter; Vanderhurst et al. 1982).

Coastal Features and Processes

Map units **Qbs**, **Qhb**, **Qdsy**, **Qbmy**, **Qdso**, **Qbmo**, **Qob**, **Qobs**, **Qtmr**, **Qmst**, **Qc**, **QTm**

Coastal environments—shaped by waves, tides, wind, and geology—may include tidal flats, estuaries, river deltas, wetlands, dunes, beaches, barrier islands, bluffs, headlands, and rocky tidepools. Golden Gate National Recreation Area has 146 km (91 mi) of shoreline. This figure by Curdts (2011) includes Fort Point National Historic Site, as well as San Francisco Maritime National Historical Park; Muir Woods National Monument does not have any shoreline. Altogether, the National Park Service manages 85 ocean, coastal, and Great Lakes parks with more than 18,000 km (11,200 miles) of shoreline (Curdts 2011). More than 120 parks are close to the coast, even though some do not manage a shoreline, and are vulnerable to sea level rise, lower lake levels, salt water intrusion, and inundation during coastal storms (Beavers et al. in review). The NPS Geologic Resources Division Coastal Geology website, http://go.nps.gov/grd_coastal and NPS Oceans website, https://www.nps.gov/subjects/oceans/index.htm provide additional information.

Coastal geomorphology in the park is diverse and varies widely, from cliffs and bluffs, to sandy beaches and dunes, to calm bays, estuaries, and lagoons (Pendleton et al. 2005; Sloan 2006; Dallas et al. 2013). Each setting responds distinctly to changes in sea level, tides, wave action, and storms (Sloan 2006; Dallas et al. 2013). In addition to these modern coastal environments, evidence of ancient coastlines exists in the form of sedimentary deposits such as inactive dunes and landforms such as marine terraces.

Human-made structures are also present along the coast. A summary of park assets (facilities and structures) along the coast that are vulnerable to 1 m of sea level rise was completed for 40 parks, including Fort Point National Historic Site and Golden Gate National Recreation Area, by Peek et al. (2015). That report documented 17 assets within Fort Point National Historic Site and 1,049 within Golden Gate National Recreation Area. A coastal engineering inventory was completed for the park in 2013 (Dallas et al. 2013). The inventory identified 116 coastal engineering projects in and adjacent to the park with 94 structures spanning 26 km (16 mi) of coastline. Coastal structures along the park's northern San Francisco shoreline, which extends roughly 6 km (4 mi) from the Golden Gate Bridge to Fort Mason, armor approximately 79% of the shore. At Ocean Beach, the 7-km (4-mi) -long beach is roughly 46% armored. Summaries of the coastal engineering projects identified within Golden Gate National Recreation Area are presented in Dallas et al. (2013).

There are significant resource management issues associated with coastal features and processes, as well as the human-made structures. Refer to the "Geologic Resource Management Issues" chapter for additional information.

Cliffs and Bluffs

Because the land around the park is uplifting (see "Geologic Setting and Significance" chapter), erosional features such as cliffs and bluffs are more prevalent than depositional features such as sandy beaches, dunes, bays, and estuaries. Rocky cliffs primarily form where the older, harder rocks of the Franciscan Complex intersect the shoreline. Where waves break against sea cliffs, caves, arches, and sea stacks form (figs. 8 and 34; see "Sea Caves" section). Bluffs develop in more recent sedimentary formations (**Tsu**, **Tsl**, **Tps**, **QTm**, **Qc**).

Erosion rates vary greatly from place to place depending on rock hardness and exposure to wave action (Sloan 2006). Coastal cliffs are eroded primarily by waves

Figure 34. Photograph of bedrock erosional features along the coast. Sea stacks, arches, and caves form by erosion of bedrock along the coast (fig. 37). The features in this photograph formed in the graywacke sandstone and shale (KJfss) of the San Bruno Mountain terrane west of the Cliff House at Sutro Baths. Photograph by John Graham (Colorado State University), taken December 2014.

(especially storm waves) which oversteepen and destabilize slopes (Williams 2001). Because of this steep nature, slope movements are common (see "Slope Movements" section) and the GRI GIS data show many landslide deposits (**Qls**, **Qyl**, **Qsr**) among coastal cliffs and bluffs. Groundwater seeping out of cliff faces augments the destabilizing action of waves on coastal cliffs (Williams 2001).

Coastal cliffs, such as those on Alcatraz and the Marin Headlands, contain an important environment known as the rocky intertidal zone—the band of rocky shore covered up by the highest of tides and exposed during the lowest of tides. The rocky intertidal zone hosts an extraordinarily diverse and productive ecosystem and it is also highly sensitive to pollution, invasive species, and climate change (Weinberg 2013).

Sandy Beaches

Sandy beaches in the managed area of the park include Stinson Beach, Muir Beach, Tennessee Beach, Rodeo Beach, Baker Beach, China Beach, Ocean Beach, and several other unofficially named pocket beaches (Pendleton et al. 2005). Stinson Beach is a spit of land separating Bolinas Bay from Bolinas Lagoon. Rodeo Beach is a barrier beach separating Rodeo Cove and Rodeo Lagoon. The remaining beaches are directly along the mainland north and south of the Golden Gate. Beaches are mapped primarily as beach sand (**Qbs**) and active dune sand (**Qdsy**), and in some places include undifferentiated Quaternary material (**Qu**) and artificial fill (**Qar**, **Qf1**). Sand size grains dominate most beaches, but pebble and cobble size grains are also present.

The primary sources of beach sediment are (1) offshore submerged ancient dunes that formed on land during the last ice age when sea level was lower (see the "Dunes" section and "Geologic History" chapter) and (2) erosion of local rocks (chiefly Franciscan rocks). Waves pushed the ancient submerged dune sand ashore and distributed it primarily southward. Erosion of local rocks is evident in places like Rodeo Beach where Franciscan chert and greenstone have weathered into red and green pebbles, respectively (Sloan 2006). Much of this source sediment entered the San Francisco Bay prior to its incorporation into the park's beaches (Elder 2013). Upland sediment carried by the Sacramento River is deposited closer to Sacramento and somewhat in San Francisco Bay and does not reach the park's beaches in large quantities (Dallas et al.

2013). Anthropogenic activities in San Francisco Bay have changed the amount of sediment delivery to the outer coast, primarily along Ocean Beach (see "Coastal Erosion and Sediment Dynamics" section; Dallas et al. 2013).

Beaches naturally change in size and shape seasonally (Sloan 2006). Winter storm waves tend to move sand from the beach to offshore bars, while gentler summer waves move sand from offshore bars onto the beach. Beaches, therefore, tend to be wider in the summer and narrower and lower in the winter. At Bakers Beach, prominent cusps point in the direction of rip currents and show how high-energy waves move the sand around (Sloan 2006; Will Elder, park ranger, Golden Gate National Recreation Area, written communication, 30 October 2015). Larger and more durable grains (particularly quartz sand and gravel) concentrate on the beach and finer sediments stay suspended in water longer, finally coming to rest in the quieter, deeper water farther offshore (Stoffer 2002).

Beach sands are also moved along the shore by longshore drift; along the coast of the park, sand is moved generally southward (Sloan 2006). Ocean Beach is an exception, where transport is to the north because of an eddy (Will Elder, park ranger, Golden Gate National Recreation Area, written communication, 30 October 2015).

Many of the beaches in the park have been either eroding or accreting for long periods of time. For example, the shoreline from Crissy Field to northern Ocean Beach has experienced net accretion since the late 1800s (Dallas and Barnard 2011). A majority of the exposed, open coast beaches from southern Ocean Beach to Point San Pedro have experienced erosion since the late 1800s (Dallas and Barnard 2011; Eshleman and Ward 2015), with the exception of the northern and central portions of Ocean Beach where a trend shows shoreline accretion (Barnard et al. 2007).

Wave-cut platforms and marine terraces are common features along the beaches in the park. A wave-cut platform is a gently sloping rock surface that extends from the beach out into the ocean. It is formed by the prolonged action of waves against the edge of the land during extended periods of steady sea level. Wave-cut platforms are often covered in beach sand deposits (**Qbs**). In some locations, the platform is visible during low tide.

Along tectonically active coasts like those of the park, the wave-cut platform may be uplifted to form a relatively flat area called a marine terrace (Sloan 2006). If uplift occurs repeatedly, several levels of marine terraces, each progressively older and higher, form landward of the shore (Sloan 2006). This is very common along the Pacific Coast (Pampeyan 1994). For instance, the sea cliffs at Fort Funston (fig. 23) expose the Merced Formation (**QTm**), the sediments of which originally accumulated in the low coastal zone (Stoffer 2002). The Fort Funston marine terrace is about 100,000 years old and once extended several miles west across the continental shelf. Marine terraces along the ocean coast of the park have largely been covered in layers of alluvial, beach, and aeolian deposits (**Qtmr**). A sequence of marine terraces also existed on the bay side of the San Francisco Peninsula, but urban development has obliterated or obscured them (Pampeyan 1994).

Dunes

Dunes form by aeolian processes, which refer to windblown erosion, transportation, and deposition of sediments (Lancaster 2009). The NPS Geologic Resources Division Aeolian Resource Monitoring website, http://go.nps.gov/monitor_aeolian, provides additional information.

Dune sands (**Qdsy**) cover a large portion of the northern San Francisco Peninsula (fig. 35). In the park, active dunes are mapped in the Presidio and along the coast from Baker Beach to Mori Point. In cross section, the dunes show a sedimentary feature called cross-bedding, which indicates the direction the wind was blowing during deposition (fig. 36). Small areas of dunes are also mapped in the Marin Headlands between Rodeo Lagoon and Point Bonita.

Much of the artificial fill (**Qar**) mapped in the San Francisco North quadrangle (Presdio, Fort Point, and western portion of Marin Headlands) contains dune sand. Dune sands are also a component of beach sands (**Qbs**). Older, inactive dunes (**Qdso**) dating back at least 11,700 years (latest Pleistocene Epoch) are mapped north of Tomales Bay (outside the boundaries of the park). Marine terrace deposits (**Qtmr**), like those south of Pacifica, may include dune sand. Some older map units, such as the Pleistocene Colma Formation (**Qc**) and the Pleistocene and Pliocene Merced Formation (**QTm**), may contain sediments originally deposited in dunes (Henkel et al. 2015).

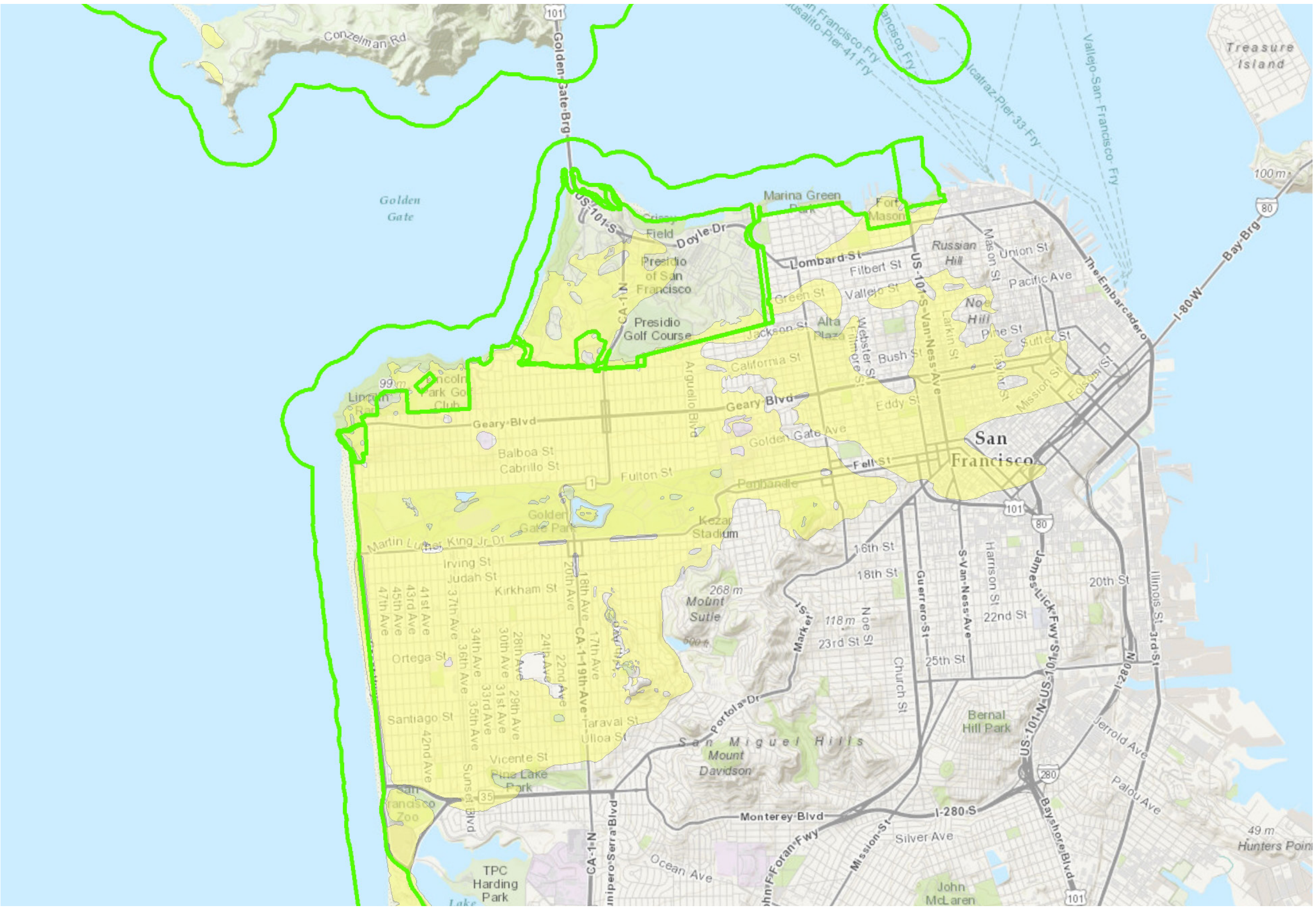


Figure 35. Map of dune sand extent. Holocene dune sands (geologic map unit Qdsy "Dune Sand, Younger") are mapped (yellow area) over much of San Francisco south of Golden Gate. The park boundary is indicated by a green line. Map by the author using GRI GIS data.

Figure 36. Photograph of cross-bedding in dunes at Baker Beach. Cross-bedding can be used to determine prevailing wind direction when the dune was active. Inclined beds indicate that the transport direction was from left to right. Photograph by Katie KellerLynn (Colorado State University), taken during the 2007 GRI scoping meeting.

Dunes are an important part of the history of the San Francisco Bay Area (see "Geologic History" chapter). Tremendous quantities of dune sand were deposited during the last ice age when sea level was about 100 m (300 ft) lower than at present (Schlocker et al. 1958; Atwater 1979; Sloan 1989). Westerly winds swept sand from a broad coastal plain that existed during the last ice age up and over the rolling hills of the San Francisco Peninsula to the east as far as Rincon Hill leaving deposits up to several hundred feet thick; deposits are much thicker on the east (lee) side of hills (Schlocker et al. 1958; Atwater 1979). These sand dunes once formed one of the most extensive coastal dune systems on the West Coast (Elder 2001). As sea level rose toward the end of the last ice age, many of the dunes were submerged, such as Potato Patch shoal off the Golden Gate. Today, these submerged dunes provide sand to the park's beaches (see "Sandy Beaches" section). Historically, Ocean Beach had a wide dune field that stretched toward downtown San Francisco (Dallas et al. 2013). Development has removed many of these dunes. Today, the largest remaining active dune field is at Fort Funston.

Plants that are specially adapted for growth in the shifting sands of a harsh dune landscape thrive in several locations throughout the park. A small remnant of an ancient dune ecosystem survives mainly within the Presidio and a preserved and restored dune habitat exists at Baker Beach and Lobos Creek Valley (Elder 2001). The coastal dune scrub community provides food and shelter for insects, reptiles, birds, and mammals. It includes several rare plants, such as the dune gilia (*Gilia capitata* ssp. *chamissonis*) and San Francisco lessingia (*Lessingia germanorum*) (Elder 2001).

Estuaries and Bays

Estuarine and bay mud deposits are mapped in the park primarily surrounding Tomales Bay, with a small deposit mapped at the south end of Upper Crystal Springs Reservoir (**Qhb**). These units consist chiefly of fine-grained sediments such as silt and clay deposited at or near sea level. They also typically contain organic matter, which produces a blue-gray to black appearance.

In the GRI GIS data, Crissy Field is mapped primarily as artificial fill (**Qar**) and beach sand (**Qbs**). However, it was historically a salt marsh and estuary. Its artificially filled wetlands contributed to a "system-wide trend of ecosystem degradation, habitat loss and tidal prism alteration" (Dallas et al. 2013, p. ix). Restoration efforts have returned the site to a more natural state (see "Disturbed Land Restoration" section; Dallas et al. 2013)

San Francisco Bay is the largest estuary on the west coast of the United States. It drains more than 40% of the state of California and connects the Sacramento River and its tributaries to the Pacific Ocean. Bolinas Lagoon is a tidal estuary. The lagoon sits behind Bolinas Bay in a valley created by the San Andreas Fault, which runs directly through it. The eastern shore of Bolinas Lagoon is within the park. Rodeo Lagoon sits behind Rodeo Beach and, unlike Bolinas Lagoon, tides do not have a significant effect on Rodeo Lagoon. It only empties into the Pacific Ocean when water levels are high enough to erode a channel through the beach, which tends to occur only in winter.

Sea Caves

As of December 2015, cave or karst resources are documented in at least 159 parks, including Golden Gate National Recreation Area. The NPS Cave and Karst website, https://www.nps.gov/subjects/caves/index.htm, provides more information.

All of the known caves in the park are sea caves and as such are limited to the coastline. A cave is any naturally occurring underground void. That definition includes sea caves as well as solutional (commonly associated with limestone and karst topography), lava tube (in lava flows), talus (a void among collapsed boulders), regolith (formed by soil piping), and glacier (ice-walled) caves (Toomey 2009). Conditions in the park may allow for the formation of talus or regolith caves, but none have been documented. The park contains little limestone and no karst or pseudo-karst (Land et al. 2013); therefore solutional caves are not likely. The conditions for lava tube or glacier caves do not exist in the area of the park.

Sea caves are a common feature in the cliffs up and down the coastline of California. The exact number of caves in the park is not known but is likely at least 100 and potentially more than 500 (Garrett and Williams 2008; KellerLynn 2008). Due to accessibility challenges, an official cave inventory has not yet been completed. Some of the caves become accessible by foot during low tide while many others are only ever accessible by boat or kayak. Garret and Williams (2008) reviewed aerial photographs in search of sea caves; planning for a field-based inventory of sea caves is in progress (see "Geologic Resource Management Issues" chapter).

Sea caves form by erosion of cliff-forming rocks in high-energy tidal zones (fig. 37). Waves and the sediments they carry exploit and enlarge weak zones such as joints, faults, dikes, veins, and layers of soft rock in otherwise erosion resistant rock. Field reconnaissance suggests sea caves are more common in the hard rocks of the Franciscan Complex ("**K**" and "**KJ**" map units) than in the softer sedimentary rocks of the Cenozoic Era ("**Q**", "**QT**", and "**T**" map units). The inside of a sea cave is often larger than the opening due to the "blasting away" of interior rocks that occurs as air is compressed when waves enter the cave (Garrett and Williams 2008). Some cave enlargement may even be attributed to the boring action of tidal creatures such as chitons and echinoderms (Moore 1954).

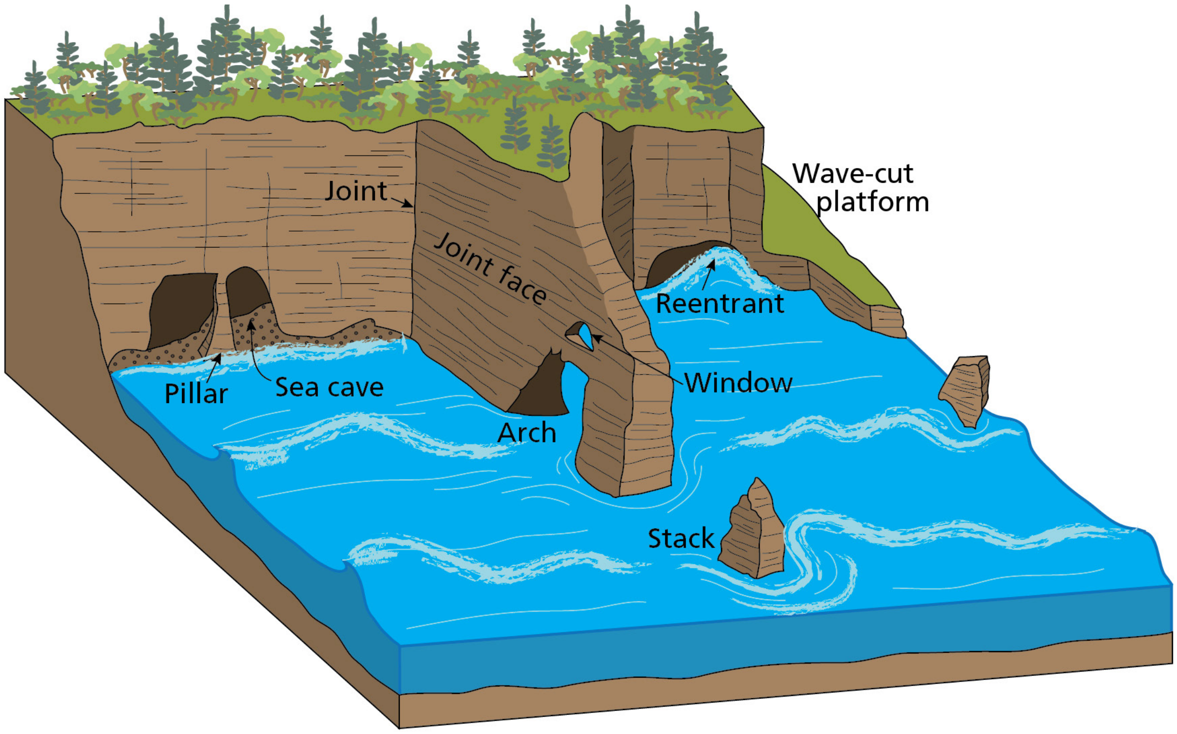


Figure 37. Illustration of coastal erosional features. Sea caves are erosional features that form in high energy tidal environments. Waves and the sediments they carry exploit and enlarge weak zones such as joints, faults, dikes, veins, and layers of soft rock in otherwise erosion resistant rock. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

Dissolution of water soluble rocks such as limestone may also contribute to sea cave formation (Moore 1954). The GRI GIS data only show coastal limestone (**KJfl**) just south of Mori Point, in a location outside of the NPS-managed area in the park. However, local conditions where dissolution could occur may exist along the coast such as in the case of carbonate veins in the widespread outcrops of mélange (**KJfm**), carbonate beds in Paleocene sandstone (**Tsu**) at Point San Pedro, and inclusions of silica-carbonate rocks in serpentinite (**KJfsu**) at Fort Point National Historic Site.

Sea caves rarely contain speleothems (cave formations), though some flowstone or small stalagmites may occasionally be observed (Bunnell 2013). Sea caves in the park do develop coatings of white or earth-tinted minerals such as calcite, gypsum, halite, tarnakite, vashegyite, opal, leucophosphite, francoanalite, red-orange tinted goethite, and bright yellow jarosite (Bruce Rogers, US Geological Survey, cave specialist, email communication, 12 June 2008, cited in Garrett and Williams 2008, p. 2).

Many types of organisms inhabit or use sea caves. Common tide-pool invertebrates such as algae, amphipods, barnacles, copepods, anemones, starfish, sponges, limpets, and mussels can be found in caves. In addition, specially adapted organisms may be present in the dark zone of a sea cave such as the sea cave isopods *Ligia pallasii* and *L. occidentalis* (Renate Eberl, Santa Rosa Junior College, adjunct faculty, personal communication, 22 August 2008, cited in Garrett and Williams 2008, p. 2). Some sea anemones and sea sponges found in the dark zone of sea caves lack pigment and appear white. Sea caves with deep enough water may provide habitat for sharks and other fish. Birds and marine mammals such as seals and sea lions may also utilize sea caves (Dan Richards, Channel Islands National Park, marine biologist, email communication, 24 June 2008, cited in Garrett and Williams 2008, p. 2; KellerLynn 2008; Bunnel 2013). Surge channels—channels in a rocky shoreline through which waves pass in and out—may connect to caves and provide good habitat for fish, abalone and other intertidal animals (Will Elder, Golden Gate National Recreation Area, park ranger, written communication, 30 October 2015).

Geologic Resource Management Issues

This chapter describes geologic features, processes, or human activities that may require management for visitor safety, protection of infrastructure, and preservation of natural and cultural resources in Golden Gate National Recreation Area, including Fort Point National Historic Site and Muir Woods National Monument. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

Park managers face increasingly difficult challenges as the urban population of the surrounding San Francisco Bay Area continues to grow, placing a mounting number of visitors in contact with an already geologically dynamic and at times unstable natural environment. Past and continuing slope instability, coastal erosion, and active faulting are some of the geologic issues inherent to the area.

Many geologic issues have been and should continue to be addressed through coordinated efforts with local, state, and other federal agencies as well as the public. Each entity's role is complex and roles are often overlapping (Williams 2001). One of the most common and difficult challenges is deciding how to best direct limited personnel and funding.

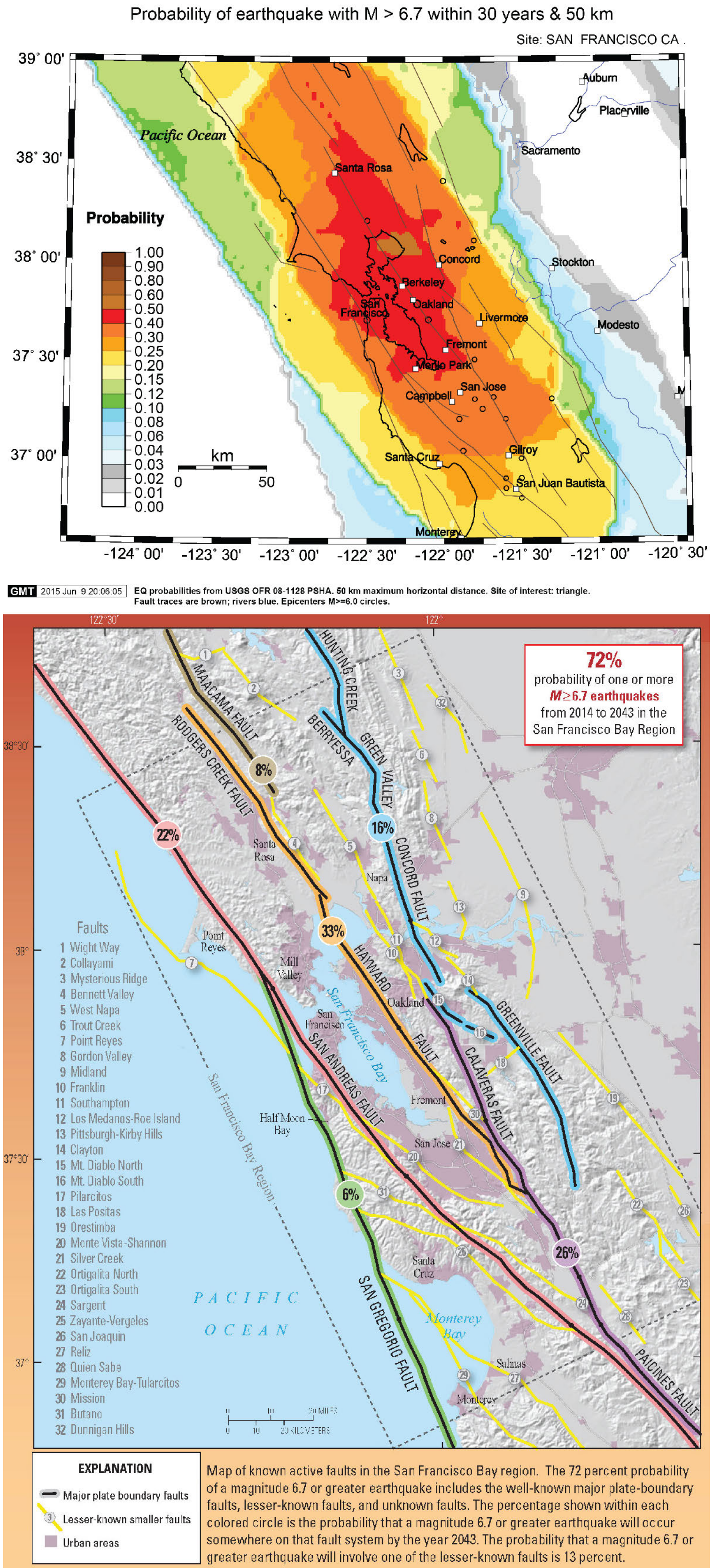
During the 2007 scoping meeting (see scoping summary by KellerLynn 2008) and 2014 conference call, participants (see Appendix A) identified the following geologic resource management issues:

- Earthquake Probability, Hazards, and Risks
- Slope Movement Hazards and Risks
- Flooding
- Sea Level Rise
- Coastal Resource Management and Planning
- Coastal Erosion and Sediment Dynamics
- Marine Features and Offshore Mapping
- Sea Cave Documentation and Management
- Paleontological Resource Inventory, Monitoring, and Protection
- Monitoring Aeolian Resources
- Geothermal Resource Protection
- Coastal Serpentine Scrub Preservation
- Disturbed Land Restoration
- Naturally Occurring Hazardous Materials
- Groundwater Contamination
- Abandoned Mineral Lands
- External Energy and Mineral Development
- Renewable Energy Development

The 2013 State of California's multi-hazard mitigation plan addresses many of the issues discussed in this chapter (see http://www.caloes.ca.gov/cal-oes-divisions/hazard-mitigation/hazard-mitigation-planning/state-hazard-mitigation-plan). Resource managers may also find *Geological Monitoring* (Young and Norby 2009) useful for addressing some of these issues. *Geological Monitoring* is available online at http://go.nps.gov/geomonitoring. The manual 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 and suggested monitoring methods.

Earthquake Probability, Hazards, and Risks

A serious earthquake will affect the San Francisco Bay Area in the next few decades. Probabilities for a strong (magnitude 6.7 or greater) earthquake in or near the park within the next 30 years are between 0.30 and 0.50 (a 30% to 50% "chance"; fig. 38). According to a June 2016 US Geological Survey fact sheet, there is a 0.72 probability for such an earthquake somewhere in the San Francisco Bay Region before 2043 (fig. 38; Aagard et al. 2016). Earthquakes cannot be prevented and prediction is imprecise; therefore, preparedness is imperative to minimize risk associated with earthquake hazards. Earthquake hazards include damage or destruction of structures, natural resources, or cultural resources due to shaking, creep, surface rupture, liquefaction, tsunamis, or earthquake-induced landslides. Risk is the probability of occurrence combined with the expected degree of damage or loss that may result from exposure to a hazard, or the likelihood of a hazard causing losses (see Holmes et al. 2013). Risk is highest in the park where visitation is high and in or near structures or features



susceptible to damage by at least one of the aforementioned hazards. Detailed information is provided by earthquake scenarios that estimate the scale and extent of damage, social disruption, and economic losses due to potential earthquakes (see Chen et al. 2011).

Many organizations and resources are available to assist park staff with earthquake preparation and planning. Zones of required investigation for possible earthquake faulting, landslides, and liquefaction are delineated by the California Geological Survey (CGS) and distributed to cities, counties, and state construction agencies to help identify where higher building standards may be necessary for safe development. The CGS Regulatory Hazard Zones website, http://www.consrv.ca.gov/cgs/geologic_hazards/regulatory_hazard_zones/Pages/Index.aspx, provides more information. The Alquist-Priolo Earthquake Fault Zoning Act requires identification of surface trace of active faults and is intended to prevent the construction of buildings used for human occupancy in those zones. That act only addresses the hazard of surface fault rupture and is not directed toward other earthquake hazards such as liquefaction and earthquake induced landslides that are addressed by the Seismic Hazards Mapping Act of 1990. The Association of Bay Area Governments (ABAG) and Bay Conservation Development Commission (BCDC) manage a resilience program to

Figure 38. Earthquake probability maps. Top: Map shows the probability of an earthquake with magnitude >6.7 in the next 30 years. Graphic generated using the US Geological Survey earthquake probability mapping program (https://geohazards.usgs.gov/eqprob/2009/index.php; accessed 9 June 2015). Bottom: Map of known active faults in the San Francisco Bay region. US Geological Survey map extracted from Aagaard et al. (2016), page 1; http://dx.doi.org/10.3133/fs20163020; accessed 6 July 2016.

promote preparedness and rapid recovery from the effects of earthquakes and natural hazards (see http://resilience.abag.ca.gov/). In the *Geological Monitoring* chapter about earthquakes and seismic activity, Braile (2009) described the following methods and vital signs for understanding earthquakes and monitoring seismic activity: (1) monitoring earthquakes, (2) analysis and statistics of earthquake activity, (3) analysis of historical and prehistoric earthquake activity, (4) earthquake risk estimation, (5) geodetic monitoring and ground deformation, and (6) geomorphic and geologic indications of active tectonics. The US Geological Survey Earthquakes Hazards website, http://earthquake.usgs.gov/, provides more information. Park managers also may consult the California Geological Survey (e.g., see California Geological Survey 2008), California Emergency Management Agency, and California Seismic Safety Commission.

The National Park Service invested tens of millions of dollars retrofitting buildings to withstand seismic hazards at the park. For instance, in 2007 Yerba Buena Engineering & Construction began rehabilitating the foundations of 18 historic buildings at Fort Cronkhite. Historic structures such as the water tower at Alcatraz and buildings at the Presidio and Fort Mason have also been retrofitted to improve resilience to earthquakes (Tamara Williams, Golden Gate National Recreation Area, hydrologist, personal communication, 13 October 2015). The California Department of Transportation, San Francisco Metropolitan Transportation Agency, and the Golden Gate Bridge District have invested hundreds of millions of dollars in seismic upgrades to the Golden Gate Bridge and Highway 1 (US 101) through the park (Tamara Williams, personal communication, 13 October 2015).

Earthquake Probability

Probability is the first step to assessing hazards. Currently, the US Geological Survey assesses earthquake potential with a model—the Uniform California Earthquake Rupture Forecast (UCERF). As of 10 May 2016, the model is on version 3 (UCERF3; see Field et al. 2015). UCERF3 provides authoritative estimates of the magnitude, location, and likelihood of earthquake fault rupture throughout the state. The UCERF3 group chose a magnitude-6.7 earthquake and the "next 30 years" because the 1994 Northridge earthquake, which ruptured the surface, was a 6.7 magnitude quake, and 30 years is the typical length of a homeowner's mortgage (Field et al. 2015). The Northridge earthquake caused an estimated 60 fatalities and more than $20 billion in damage. Significant changes from the previous UCERF model include reduced likelihood of moderate-sized earthquakes and increased likelihood of large earthquakes (Field et al. 2015). The estimate for the likelihood that California will experience a magnitude 8 or larger earthquake in the next 30 years has increased from about 4.7% for UCERF2 to about 7.0% for UCERF3 (Field et al. 2015).

As this report was in final review, the US Geological Survey released Fact Sheet 2016-3020: *Earthquake Outlook for the San Francisco Bay Region 2014–2043* (Aagard et al. 2016). Using information from recent earthquakes, improved mapping of active faults, and a new model for estimating earthquake probabilities, the 2014 Working Group on California Earthquake Probabilities updated the 30-year earthquake forecast for California. They concluded that there is a 72 percent probability (or likelihood) of at least one earthquake of magnitude 6.7 or greater striking somewhere in the San Francisco Bay region before 2043 (fig. 38). The publication includes links to additional information and tips for earthquake preparedness.

Recent rupture reduces the likelihood of another earthquake in the near future because it takes considerable time for tectonic stress to rebuild (Field et al. 2015). For example, the segment of the San Andreas Fault that runs closest to the park has a relatively low, 6.4%, chance of having a magnitude 6.7 or greater earthquake in the next 30 years compared to other faults in the area because the 1906 San Francisco earthquake released much of this stress (Field et al. 2015). The Hayward Fault has the highest probability of such an earthquake in the Bay Area (fig. 38). It is mapped outside the park, but a strong earthquake on the fault will likely impact park resources. Many of the faults in the area are seismically connected, meaning that a slip along one could generate movement in another. For example, shaking from the 1989 Loma Prieta earthquake clearly reactivated some fissures that were originally observed from the 1906 San Francisco earthquake (Ellsworth 1990).

Shaking, Creep, and Surface Rupture

The next step to assessing earthquake hazards is estimating the relative amount of ground shaking expected from a likely earthquake. The entire park (and

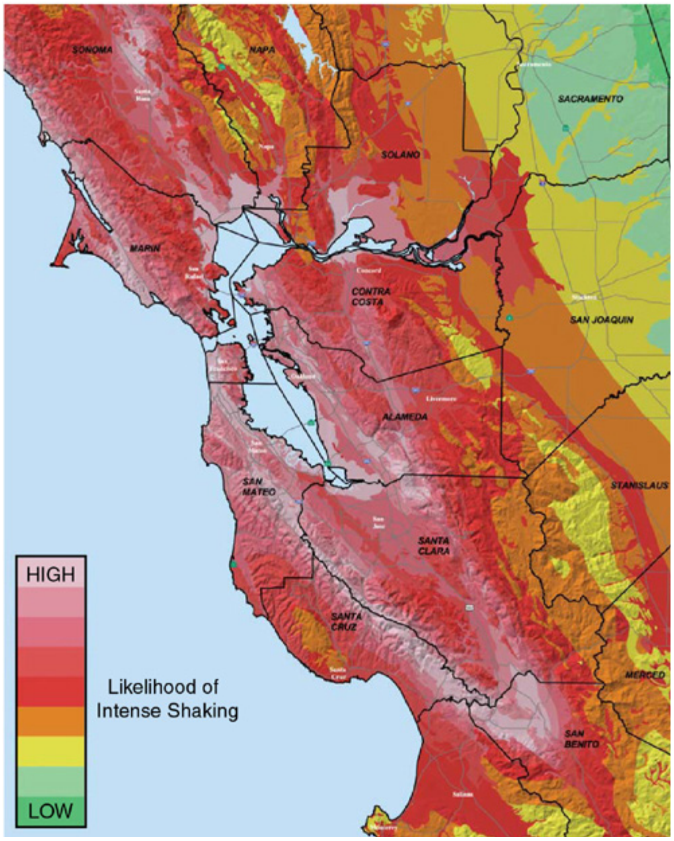


Figure 39. Map of earthquake shaking potential for the San Francisco Bay Area. The map shows the expected severity of ground shaking and damage in the San Francisco Bay Area from anticipated future earthquakes. Intense shaking can damage even strong, modern buildings. Data Sources: California Seismic Safety Commission, California Geological Survey, Governor's Office of Emergency Services, and United States Geological Survey, April 2003, Earthquake Shaking Potential for California, California Seismic Safety Commission Publication No. 03-02. Major roads from Thomas Brothers Maps, Inc., 2000, 2001. Shaded relief from US Geological Survey 30-meter DEM. Available at http://www.seismic.ca.gov/pub/intensitymaps/sfbay_county_print.pdf and http://geomaps.wr.usgs.gov/sfgeo/liquefaction/aboutliq.html#shakefig.

indeed all of the San Francisco Bay Area) has the highest level of relative risk for earthquake shaking intensity and damage, as mapped by the California Geological Survey (2003) (fig. 39). Quantitative details regarding projected intensity and likelihood of shaking are available for the whole country from the US Geological Survey (Petersen et al. 2015).

The strength of earthquake shaking at a particular location is mainly the result of three factors: underlying soil/rock/deposit type, the earthquake's magnitude, and distance from the source fault. Unconsolidated units such as artificial fill are particularly susceptible to the most intense earthquake shaking whereas hard bedrock such as granite experiences less intense shaking (e.g., Lawson 1908; Borcherdt et al. 1975; Brabb et al. 2000). Unconsolidated units that have a significant amount of water are also subject to liquefaction (described below). Within the park, shaking will be intense across all geologic map units and will be strongest in unconsolidated Quaternary ("**Q**") map units. Where those map units are located beneath significant infrastructure (e.g., facilities, roads, trails, and historic structures), the risk for damage is even higher. A shaking-related hazard of particular concern at Muir Woods National Monument is the snapping off of limbs and falling of redwood trees (fig. 40; KellerLynn 2008). The Cliff House, the Presidio, the south end of Golden Gate Bridge, and Tamalpais Peak are sites included in the California Strong Motion Instrumentation Program, which records the strong shaking of the ground and in structures during earthquakes through a statewide network of strong motion instruments (see http://www.conservation.ca.gov/cgs/smip).

Creep also impacts infrastructure that crosses faults. For example, creep along the Hayward Fault in Contra Costa and Alameda counties offsets and deforms curbs, streets, buildings, and other structures. Surface ruptures are a dramatic illustration of movement along a fault, offsetting structures built across the fault (fig. 28).

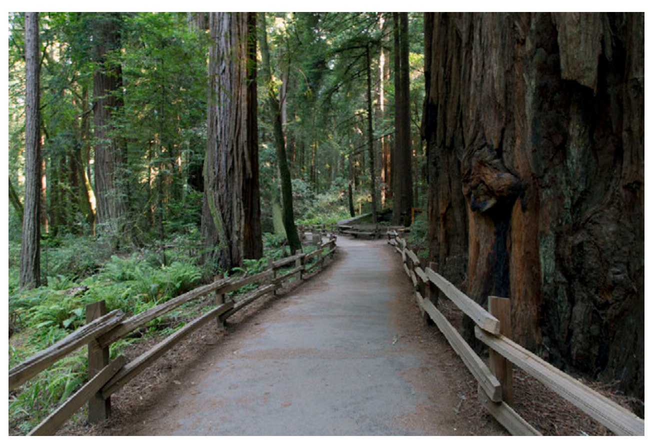


Figure 40. Photograph of trail among redwood trees at Muir Woods. Shaking from earthquakes can cause tree limbs to break and fall to the ground. Photograph from the Jon B. Lovelace Collection of California Photographs in Carol M. Highsmith's America Project, Library of Congress, Prints and Photographs Division, available at https://lccn.loc.gov/2013632551 (accessed 1 July 2016).

Surface ruptures are the most easily avoided seismic hazard (US Geological Survey 2006). The primary strategy to reduce risk associated with creep and surface rupture is to avoid building infrastructure across mapped faults.

Liquefaction

Ground shaking during an earthquake can cause water saturated sediments to flow like a liquid ("liquefaction") and become unable to support overlying structures like bridges and buildings (fig. 41). The following three elements are required for liquefaction: (1) the presence of loose, granular sediment, which is typically either young deposits or manufactured land ("artificial fill"); (2) saturation of the sediment by groundwater, particularly when levels are within 12 m (40 ft) of ground surface; and (3) strong shaking. The San Francisco Bay Area is underlain by young dune sands from the last ice age. The ground is commonly saturated in winter and spring following the "wet season." All of the San Francisco Bay Area is susceptible to shaking strong enough for liquefaction to occur.

Figure 41. Photograph of liquefaction-related damage from the 1906 earthquake. This home at Howard and 17th streets (Mission District) is underlain by marsh deposits that were covered by artificial fill in the middle to late 1800s. Earthquake shaking caused the artificial fill to liquefy and lose its ability to support the house. US Geological Survey photograph by G. K. Gilbert.

Liquefaction hazard is particularly acute around the margin of San Francisco Bay; significant damage has occurred in these locations during previous large earthquakes (Ellsworth 1990; Sloan 2006). As far back as the 1868 Hayward Fault earthquake, engineers recognized the hazards of building on water saturated "made ground" reclaimed from the San Francisco Bay (Ellsworth 1990). Areas of old fill were the most severely damaged during the 1906 San Francisco earthquake. Unfortunately, knowledge of this susceptibility did not significantly alter development patterns, and the same areas were damaged again in the 1989 Loma Prieta earthquake.

Indeed, the highest hazard areas shown by liquefaction hazard maps (fig. 42) are concentrated in regions of artificial fill, especially fill that was placed many decades ago in areas that were once submerged (former bay floor). Other potentially hazardous areas include those along some of the larger streams, which produce loose young soils (Witter et al. 2006). Such materials perform poorly even under modest levels of shaking and can localize damage to specific areas (Lawson 1908). For example, the portions of Interstate 880 in Oakland that collapsed in the 1989 Loma Prieta earthquake were constructed on soft estuarine sediments (**Qmf**, **Qu**) (Ellsworth 1990). By contrast, sections constructed on alluvium (see Map Unit Properties Table, in pocket) did not collapse.

The most recent liquefaction susceptibility maps for the San Francisco Bay Area were published by the US Geological Survey and California Geological Survey in 2006 (Witter et al. 2006). Those maps did not cover northern San Francisco (e.g., Fort Point National Historic Site) or the Marin Headlands because updated mapping was still underway. Knudsen et al. (2000) provided regional scale mapping for both Marin Headlands (primarily "low potential" except for river valleys where susceptibility is high) and northern San Francisco (mostly "very high" potential). State of California (2000) published a detailed map of liquefaction susceptibility for northern San Francisco. Susceptible areas in the park include Fort Mason, Crissy Field, Fort Point National Historic Site, Baker Beach, Ocean Beach, and Fort Funston (fig. 42).

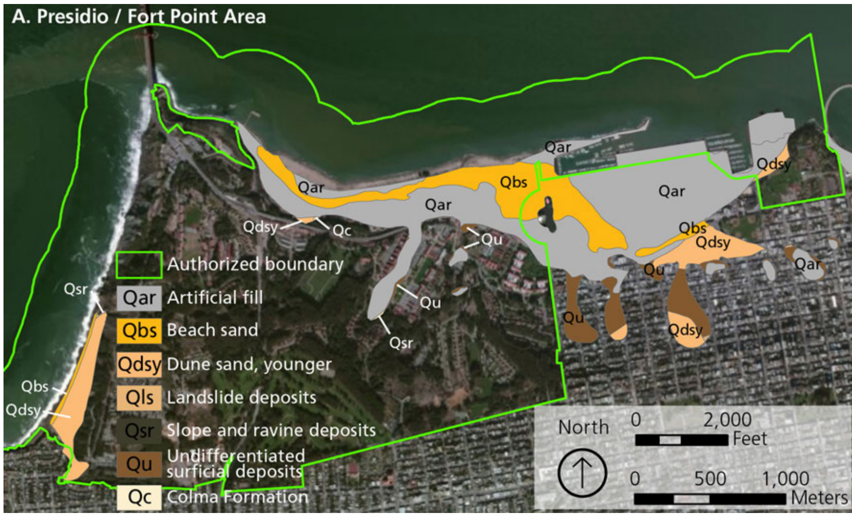


Figure 42. Maps of liquefaction "Zones of Required Investigation." The maps show the locations that were classified by the California Geological Survey (2000) as liquefaction hazard zones. The GRI GIS units within those areas are shown here. These are areas "where historic occurrence of liquefaction or local geological, geotechnical, and groundwater conditions indicate a potential for permanent ground displacements such that mitigation as defined in Public Resources Code Section 2693(c) would be required." Map compiled by the author using California Geological Survey (2000) data and GRI GIS data. Aerial image by Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

Mitigating the hazards and risk associated with liquefaction is accomplished through a variety of approaches, including: (1) avoiding building in hazardous areas; (2) purchasing insurance to cover anticipated losses; (3) "improving" the ground so it is less susceptible to liquefaction, or if liquefaction does occur, the amount of surface deformation is reduced; and (4) fortifying structures to withstand liquefaction of underlying soils (US Geological Survey 2006). Table 4 shows some of the ground improvement and structural solutions that are available to reduce hazard from liquefaction.

Earthquake-Induced Landslides

Landslides are a natural process in the Bay Area (see "Landslide Deposits and Slope Movements" section). Earthquake damage is most severe when shaking is compounded by ground failures such as landslides (Ellsworth 1990; California Geological Survey 2000). Areas that are most susceptible to earthquake-induced landslides are steep slopes in poorly cemented or highly fractured rocks; areas underlain by loose, weak soils; and areas on or adjacent to existing landslide deposits (California Geological Survey 2000). State of

Table 4. Ground improvement and structural solutions available to reduce hazards from liquefaction.

General Category	Mitigation Methods	Notes
Excavation and/or compaction	• Excavation and disposal of liquefiable soils • Excavation and recompaction • Compaction (for new fill)	None
In-situ ground densification	• Compaction with vibratory probes (e.g., Vibroflotation, Terraprobe) • Dynamic consolidation • Compaction piles • Deep densification by blasting • Compaction grouting	• Can be coupled with installation of gravel columns • Can also provide reinforcement
Selected other types of ground treatment	• Permeation grouting • Jet grouting • Deep mixing • Drains (gravel, sand, or pre-fabricated strip drains) • Surcharge pre-loading • Structural fills	Many drain installation processes also provide in-situ densification
Berms, dikes, sea walls, and other edge containment structure/systems	• Structures and/or earth structures built to provide edge containment and thus to prevent large lateral spreading	None
Deep foundations	• Piles (installed by driving or vibration) • Piles (installed by drilling or excavation)	Can also provide ground densification
Reinforced shallow foundations	• Grade beams • Reinforced mat • Well-reinforced and/or post-tensioned mat • "Rigid" raft	None

Source: table 2 from Seed et al. (2001)

California (2000) produced a detailed seismic hazard map of northern San Francisco that includes areas susceptible to earthquake-induced landslides. Susceptible areas in the park include slopes within Fort Point National Historic Site, the Presidio, Land's End (China Beach and Ocean Beach), and Fort Funston (fig. 43). Regional landslide susceptibility maps that encompass the park are summarized in the "Slope Movement Hazards and Risks" section. Monitoring and management options are also discussed in that section.

Tsunamis

Earthquakes under the ocean may generate large waves called tsunamis. Earthquakes generated hundreds or thousands of kilometers away could produce tsunamis that may affect the park. Local faults that could trigger tsunamis include the Point Reyes thrust fault, Rodgers Creek–Hayward Faults and San Gregorio Fault.

All beaches lagoons and other coastal features in the park are in tsunami inundation areas. The California Geological Survey created tsunami inundation maps. These are available at http://conservation.ca.gov/cgs/geologic_hazards/Tsunami/Inundation_Maps/Pages/Statewide_Maps.aspx. To develop these maps, the California Geological Survey considered earthquakes from the Cascadia Subduction Zone (northern California, Oregon, Washington, and British Columbia), Aleutian Subduction Zone (Alaska), and plate boundaries in Chile, Japan, Kuril Islands (Russia), and the Marianas. The National Tsunami Warning Center based in Palmer, Alaska, issues tsunami warnings, watches, or advisories in response to earthquakes. Additional information and current status are available at http://wcatwc.arh.noaa.gov/.

Slope Movement Hazards and Risks

Landslide deposits have been mapped throughout the park (see "Landslide Deposits and Slope Movements" section). Landslide hazard assessment and mitigation is particularly significant for the cultural preservation of many coastal fortifications (e.g., Fort Funston, the Presidio, and Alcatraz). Rockfall, a type of slope movement, on the coastal cliffs of Alcatraz are an example of a threat to historic structures as well as infrastructure and visitor safety (figs. 44 and 45).

In the *Geological Monitoring* chapter about slope movements, Wieczorek and Snyder (2009) described five vital signs for understanding and monitoring

Figure 43. Maps of earthquake–induced landslide hazard zones. The maps show the locations of the geologic units in the park that were also classified by the California Geological Survey (2000) as earthquake-induced landslide hazard zones. These are areas "where previous occurrence of landslide movement, or local topographic, geological, geotechnical and subsurface water conditions indicate a potential for permanent ground displacements such that mitigation as defined in Public Resources Code Section 2693(c) would be required." Map compiled by the author using California Geological Survey (2000) data and GRI GIS data. Background image by Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

slope movements: (1) types of landslide, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessment of landslide hazards and risks. In addition, the NPS Geologic Resources Division Geohazards (http://go.nps.gov/geohazards) and Slope Movement Monitoring (http://go.nps.gov/monitor_slopes) websites provide detailed information regarding slope movements, monitoring, and mitigation options.

The US Geological Survey created a digital database of the distribution of slides and earth flows and of the source areas of debris flows (see http://landslides.usgs.gov/state_local/sanfrancisco.php). These data also can be viewed online through the Association of Bay Area Government's earthquake and hazards program GIS viewer at http://gis.abag.ca.gov/website/Hazards/?hlyr=existingLndsld. The US Geological Survey also produced a guide to understanding landslides (Highland and Bobrowsky 2008), which provides basic landslide information, guidance on evaluating and communicating landslide hazards, and mitigation techniques for various types of landslides. The US Geological Survey landslides website (http://landslides.usgs.gov/) provides additional information.

Fires denude vegetation which can further destabilize slopes. The State of California, Department of Conservation, provides an online map service (http://maps.conservation.ca.gov/cgs/firelandslide/) that shows fire perimeter and deep landslide susceptibility. This map service is based on work by Wills et al. (2011).

Figure 44. Photographs of hazards on Alcatraz Island. Left: Photograph shows where erosion is undercutting the top of the cliff and has exposed and damaged pipes at the old parade grounds. The view is to the west from the old parade grounds. Right: Photograph shows the road that connects the old parade grounds to the walkway, which was closed as of 7 January 2015 on account of rocks falling onto the road and causing a safety issue. The fence at the base of the cliff has been damaged by falling rocks. The view is to the north from the eastern end of the old parade grounds. Photographs by John Graham (Colorado State University), taken December 2014.

Figure 45. Photograph of cliff stabilization on Alcatraz Island. This photograph shows the first phase of cliff stabilization, below the Warden's House. Phase 1 is complete. Phase 2, which extends the stabilization around the entire south face of the cliff, was underway as of 30 October 2015. National Park Service photograph by Kirke Wrench (Golden Gate National Recreation Area, date unknown).

Susceptibility

Intense rainfall and earthquakes are common landslide triggers in the San Francisco Bay Area. Certain areas and rock types in the park are more susceptible to landslides than others during times of intense rainfall and/or earthquakes. Areas of steep slopes and weak rocks are typically the most susceptible, though slides may occur on slopes graded as low as 15% if the conditions are right (California Governor's Office of Emergency Services 2013). Steep slopes occur naturally along much of the coastline of the park, including Alcatraz, and Fort Point National Historic Site. Steep slopes may also be "created" by human activities, such as road cutting, especially in the Marin Headlands. Roadways present a particular set of slope movement–related issues (see "Roadways" section). Other human activities, such as equipment loading, undercutting of slopes, human-caused fires, vegetation removal, development, or activities that alters surface and subsurface drainage patterns can exacerbate landslide hazards (Spittler 2005; Kellerlynn 2008).

Weak and highly fractured rocks in the park, including mélange (**KJfm**), serpentinite (**KJfsu**), and landslide deposits (**Qol**, **Qsr**, **Qls**, **Qyl**), are the most susceptible to further landslides (Pampeyan 1994). "Shear zones" (see "Geologic Observation Localities" layer in the GRI GIS data), typically in serpentinite and Franciscan rocks, are associated with slope movements and may be reactivated by wave action, if on the coast, or heavy rainfall. The largest landslides are in sheared serpentinite and rocks of the Franciscan Complex (Schlocker et al. 1958). Shear zones occur at Land's End and just north of the Golden Gate along Highway 1/US 101.

Graywacke (**Kfgwy**, **KJfmss**) in Marin County seems to be more prone to landslides than their counterparts north of Marin County (not on the GRI map). The reason for this difference is not well understood (Blake et al. 2000), but according to Berkland (1964) it may be related to the presence of vermiculite—swelling clays—which forms when the graywacke weathers.

Coastal areas underlain by soft rocks such as the Purisima Formation (**Tps**) at Seal Cove, the Merced Formation (**QTm**) at Fort Funston, or the upper part of the Paleocene sandstone, shale, and conglomerate (**Tsu**) at Point San Pedro are prone to failure where wave action erodes cliffs and undercuts or steepens slopes (Pampeyan 1994).

Climate change may be impacting the rate and intensity of slope movements in the park. Park staff reported a marked increase in precipitation over the last few years, including a record 56 cm (22 in) of rain in a 24-hour period in late February 2014 (Daphne Hatch, Golden Gate National Recreation Area, chief of resource management, conference call, 6 May 2014). Average US precipitation has increased since 1900 (Melillo et al. 2014). Increased rainfall would increase landslide susceptibility park-wide.

Assessment

Detailed landform mapping is crucial for recognizing landslides (Wills 2012). The distribution of mapped landslides in the GRI GIS data serves as a good first-order indicator of future landslide activity, as discussed by Nilsen and Turner (1975). At least two factors limit this method, however: (1) slope movements are not restricted to where they have been mapped in the past (Highland and Bobrowksy 2008), and (2) bedrock geologic maps often intentionally show less than 20% of the actual landslides that affect an area because their primary purpose is to map the bedrock underneath the landslide (Chris Wills, California Geological Survey, geologist, cited in KellerLynn 2008, p. 9). A more sophisticated slope stability analysis could be performed if all landslides were mapped. An accurate analysis would also include factors known to influence landslide susceptibility such as lithologic distribution, distance from active faults, and orientation of strata, which can be derived from detailed geologic maps (Brabb et al. 2000). Soeters and van Westen (1996) provided a discussion of statistical methods for identifying slope instability. Aerial and field reconnaissance is another valuable tool for determining susceptibility to slope movements.

The California Geological Survey produces landslide maps derived from geologic maps that are specifically designed for land-use planners and decision makers in hazard mitigation and resource planning (Wills 2012). Landslide hazard maps produced from bare earth LiDAR digital elevation models (DEMs) in conjunction with aerial photographs are a valuable tool for park planners and decision makers. Such maps require more time per area to produce than using only standard aerial imagery, but the result is much more complete and accurate (Wills 2014). The California Geological Survey is in the process of digitizing old landslide maps and preparing new landslide maps for the San Francisco Bay Area. In a geologically active area such as the park, the process of landslide mapping and analysis will always be ongoing (Chris Wills, California Geological Survey, geologist, conference call, 6 May 2014).

The NPS Geologic Resources Division (GRD) provides technical assistance to park managers for slope movement–related issues in parks. Park staff has submitted technical assistance requests to GRD staff to review geologic and geotechnical reports, evaluate potential risk associated with newly acquired parcels of land, and make recommendations for avoiding or mitigating geologic hazards and geotechnical problems.

If funding permits, resource managers could consider obtaining quantitative information to assess the frequency and magnitude of rockfall (and other slope movements) in high visitation areas. GRD has expertise in assisting with designing unstable slope management programs. For individual unstable slope areas, a photomonitoring program is one possibility and can be quantitative with new photogrammetry techniques. The Geoscientists-in-the-Parks program is an option to support such a project (see http://go.nps.gov/gip). The GRD Photogrammetry website, http://go.nps.gov/grd_photogrammetry, provides examples of how photographic techniques support structural analysis of rockfall areas

Highland and Bobrowsky (2008) noted the following common, observable features that might indicate impending landslide movement:

- springs, seeps, and wet or saturated ground in previously dry areas;

- cracks in soil or rock on or at the head of slopes;
- sidewalks or slabs pulling away from structures if near a slope;
- soil pulling away from foundations;
- offset fence lines;
- unusual bulges or elevation changes in the ground, pavements, paths, or sidewalks;
- tilting telephone poles, trees, retaining walls, and fences;
- excessive tilting or cracking of concrete floors and foundations;
- broken water lines and other underground utilities;
- rapid change in stream-water levels, possibly accompanied by increased turbidity;
- sticking doors and windows and visible open spaces, indicating walls and frames are shifting and deforming;
- creaking, snapping, or popping noises from a house, building, or grove of trees; and
- sunken or down-dropped roads or paths.

Observations by park staff may help identify threats to park infrastructure and visitor safety, though landslide hazard assessments should be completed by an expert.

In many cases (i.e., when human actions are not a triggering factor), slope movements are a natural process in the park, and are also a natural element of shoreline evolution. When these processes occur naturally, they only pose risk if park visitors or infrastructure are threatened. Alerting visitors to the hazards associated with rockfall and landslides near the base of cliffs is a first step toward reducing risk. Such information could be presented via the park website, brochures, signage, and/or verbal communication from park staff.

Roadways

Slope instabilities are a common development along road cuts (Williams 2001). A classic example is the instability of Paleocene sandstone and shale (**Tsu**) along California Highway 1/US 101 in the Devil's Slide area. The first major landslide occurred around 1940 and issues persisted throughout the rest of the century. The California Department of Transportation finally determined a tunnel would be the only way to permit safe passage through the area; the Tom Lantos Tunnels opened on 25 March 2013 (fig. 46).

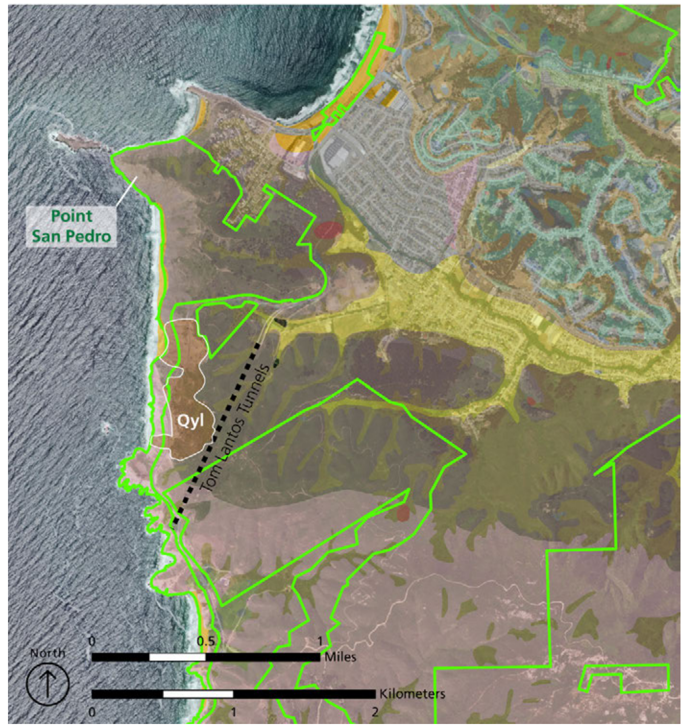


Figure 46. Map of Devil's Slide area. The first major landslide destroyed much of Highway 1, and a cycle of building and destruction followed. Landslide deposits (map unit Qyl) show the location of the repeated slope movements. The surrounding colors represent other geologic map units (see poster in pocket). In 2013, the Tom Lantos Tunnels (dashed line) opened to provide a safer route through the mountains. Map compiled by the author using GRI GIS data. Background image by Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

Tunnels are not always an option. Road cuts are often necessary in hilly terrain and have been constructed throughout the park (e.g., Conzelman Road in the Marin Headlands). Slope movements along road cuts are a hazard to visitor safety, disrupt the flow of traffic, and can be costly to clean up and repair. Slope failure at road cuts is a result of many factors, including the slope of the cut, rock type, and elevation of the groundwater table (which may be artificially enhanced by local irrigation).

Road widening and adding safety features may reduce the risk of slope failure along road cuts (Williams 2001). Drainage systems (culverts, drains, horizontal drains) can be installed to divert destabilizing water away from unstable slopes (Williams 2001). Other unstable slope mitigations can involve many types of engineered risk reduction techniques that either reduce the driving forces of instability or protect the infrastructure threatened. (Williams 2001). The appropriate mitigation measure should be decided on a case-by-case basis and in consultation with a geologic hazards specialist.

Construction in landslide-prone areas can proceed most safely by determining the site's susceptibility to slope failures and by creating appropriate landslide zoning (Highland and Bobrowksy 2008). The California Geological Survey has developed "highway corridor landslide hazard maps" to meet the needs of engineers, geologists, planners, and maintenance staff of the California Department of Transportation (see http://www.conservation.ca.gov/cgs/rghm/landslides/Pages/Index.aspx). These maps may also be useful for park staff. The California Geological Survey is in the process of developing a series of maps of selected California highway corridors within a variety of climatological and geological settings. The maps provide an inventory of landslide activity along the selected highway corridors. Such a map has not been produced for the highways in the park and is not planned at this time.

Flooding

Informed decision making requires knowledge or awareness of flood potential (Wills 2012). Unlike earthquake and slope movement hazards, the California Geological Survey is not required by state statute to produce flood potential maps, but survey staff has the data and technical skills necessary to create them as derivative products from geologic maps (Wills 2012).

Of particular concern is flood potential on alluvial fans because traditional floodplain models do not account for the shifting location of these features (Wills 2012). The California Geological Survey has produced maps of relative flood potential on alluvial fans for southern California and could possibly produce a similar product for the park.

To assist with assessing flood potential, park managers may choose to monitor fluvial geomorphology in the park. In the *Geological Monitoring* chapter about fluvial geomorphology, Lord et al. (2009) described methods for inventorying and monitoring geomorphology-related vital signs, including: (1) watershed landscape (vegetation, land use, surficial geology, slopes, and hydrology), (2) hydrology (frequency, magnitude, and duration of stream flow rates), (3) sediment transport (rates, modes, sources, and types of sediment), (4) channel cross section, (5) channel planform, and (6) channel longitudinal profile.

Coastal flooding is another potential concern for park staff, primarily because the shoreline is a popular destination for park visitors. Coastal flooding occurs during king tides (an especially high-tide event occurring several times per year), winter storms, and El Niño events (Will Elder, Golden Gate National Recreation Area, park ranger, written communication, 30 October 2015). Climate change–related sea level rise also contributes to coastal flooding. Low lying areas such as beaches are the most susceptible to coastal flooding. Refer to the "Sea Level Rise" section for more information.

Sea Level Rise

Sea level rise is caused by global climate warming in combination with regional and local effects of geologic, oceanographic, and atmospheric conditions, which vary spatially and temporally (Williams 2013). Global, or eustatic, sea level refers to the global ocean elevation. On a global scale, sea level varies with changes in the volumes of ocean basins and ocean water, caused by expansion due to heat uptake and the addition of meltwater from ice sheets and glaciers (fig. 47). Relative sea level rise, as measured by tide gauge records, refers to the combination of global rise with regional and local factors, such as rates of tectonic uplift or subsidence, sediment compaction or accumulation, and changes in ocean circulation patterns and wind patterns.

Since the 1950s, sea level has been rising at an unprecedented rate. Over the period 1901 to 2010, global mean sea level rose by 0.19 m (0.62 ft), an average rate of 1.7 mm (0.07 in) per year (IPCC 2013). Based on data from only more recent years, 1970 to 2010, the global averaged rate of sea level rise has been greater—2 mm (0.08 in) per year (IPCC 2013).

The rate of global sea level rise is very likely to increase (IPCC 2013). The newest sea level rise models and scenarios predict that global average sea level will rise by at least 0.26 m (0.85 ft) and up to as much as 1.2 m (3.9 ft) by the end of this century (Karl et al. 2009; The World Bank 2012; Church et al. 2013; US Army Corps of Engineers 2013). The National Academy of Sciences has predicted that sea level in the region that includes the park will rise between 0.42 to 1.67 m (1.38 to 5.48 ft), with 0.92 m (3.0 ft) likely, by the end of

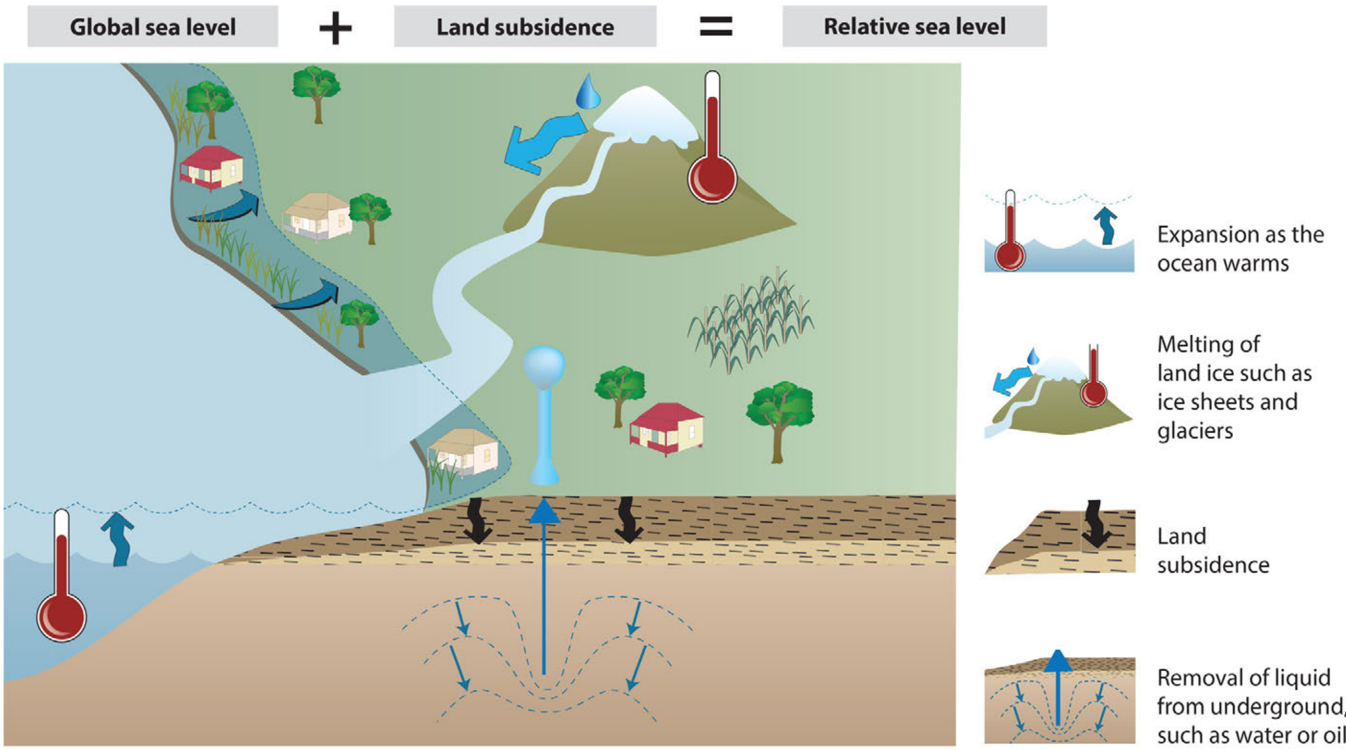


Figure 47. Illustration of the major causes of changes in sea level. Sea level rise is caused by global climate warming in combination with regional and local effects of geologic, oceanographic, and atmospheric conditions, which vary spatially and temporally. Additional causes include terrestrial water storage, building of reservoirs, changes in runoff, seepage into aquifers, vertical land movements including delta subsidence, tectonic displacements, and glacial isostatic adjustment (Williams 2013). Graphic by Jane Hawkey and Jane Thomas (Integration and Application Network, University of Maryland Center for Environmental Science) available at http://ian.umces.edu/imagelibrary/.

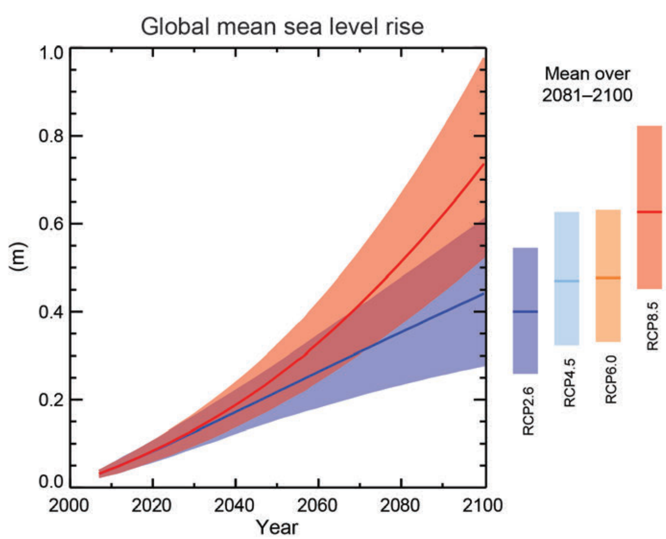


Figure 48. Graph of projected sea level rise by 2100 (in meters). Over the next century, global sea level will rise, although the magnitude of projections under various modeling scenarios varies. Graph from Church et al. (2013, figure 9).

this century (National Research Council 2012). Many recent assessments agree that a 1 m (3.3 ft) rise in global average sea level by 2100 is a reasonable value to use for planning purposes (fig. 48; Williams 2013).

Impacts of Sea Level Rise

Climate change–related sea level rise has the potential to impact many of the environmental features and processes in the park. As sea level rises, various processes modify coastlines, causing cumulative impacts at a range of spatial and temporal scales (Williams 2013). Examples of features and processes that may be impacted by rising seas include shoreline morphology, coastal erosion rates, tsunami impacts, and sea caves. The potential impacts to each feature or process is discussed in their respective sections (e.g., impact of sea level rise on sea caves is discussed in the "Sea Cave Documentation and Management" section, impact of sea level rise on coastal erosion is discussed in the "Coastal Erosion and Sediment Trends" section).

In addition to impacts on environmental features and processes, park facilities will be impacted by rising seas. The National Park Service developed a report entitled *Adapting to Climate Change in Coastal Parks: Estimating the Exposure of FMSS-Listed Park Assets to 1 m of Sea-Level Rise* (Peek et al. 2015). This report includes the location and approximate elevation of more than 10,000 assets in 40 coastal parks, based on information within the NPS Facilities Management Software System (FMSS) and supplemented with other datasets, collaboration with park staff, and field visits to locate assets. Assets were characterized based on their overall exposure to a long-term, 1 m (3 ft) rise in sea level and associated storm vulnerability, and were categorized as having either "high exposure" or "limited exposure" to the impacts of sea level rise. According to Peek et al. (2015), more than 1,000 coastal assets are mapped within Golden Gate National Recreation Area, including the Presidio, and 114 of them (11%) are considered "high exposure" to 1 m (3 ft) of sea level rise. Within Fort Point National Historic Site, which Peek et al. (2015) analyzed separately from the rest of the park's coastline, 29% of the assets (5 out of 17) are at high risk of exposure to a 1-m rise in sea level. Only the assets of the historic site near the bay were considered high exposure, primarily due to the risk of erosion (Peek et al. 2015).

Planning for Sea Level Rise

Accurate information regarding sea level rise is needed for many park management plans, project plans, and coastal adaptation strategies (see Beavers et al. in review). Predicting how sea level change will affect the park is complex and will continue to be a challenge over the next century as park managers make every effort to incorporate the latest sea level data into management plans (Caffrey and Beavers 2013). Pendleton et al. (2005) completed a Coastal Vulnerability Index (CVI) for the park that provided data for resource management and park facilities plans (see the "Coastal Resource Management and Planning" section). In addition, because the impacts of sea level rise can be exacerbated by storm surges, projected storm surge values are needed when evaluating the impacts of sea level rise (Caffrey and Beavers 2013; see "Coastal Resource Management and Planning" section).

A goal of sea level rise adaptation strategies is to simultaneously protect cultural resources and facilitate natural development of future habitat (Caffrey and Beavers 2013). Three coastal adaptation strategies for historical infrastructure such as forts and lighthouses are (1) relocate, (2) offset stressors, and (3) improve resilience; these are described by Schupp et al. (in review). The offset stressors strategy has the goal of enhancing survival of a resource while minimizing changes to the physical materials and setting of the resource(s). This is done by reducing or removing the force(s) acting on the resource or component; an example would be adding a seawall, though impacts of actions to surrounding resources, such as natural habitat or infrastructure, must be considered. Other adaptation strategies are (1) manage change, (2) document and release, (3) interpret the change, and (4) take no active intervention. Adaptation strategies take into account both FMSS-listed park assets and other NPS resources (Peek et al. 2015).

The National Park Service is also developing a *Cultural Resources Climate Change Strategy* (Rockman et al. in review), which provides an integrating framework for cultural resources and climate change that addresses inventory, significance assessment, and prioritization Additional information about the 2014 Preserving Coastal Heritage workshop to develop the strategy, and associated presentations and reports are available at https://sites.google.com/site/democlimcult/.

Tools that may be useful for determining sea level rise impacts include NOAA's hosted digital Sea Level Rise and Coastal Flooding Impacts viewer (https://coast.noaa.gov/slr/) and the US Army Corps of Engineer's Sea Level Change Calculator, which can be used with input from the San Francisco tide gauge 9414290 located near Fort Point National Historic Site and the Presidio (http://corpsclimate.us/ccaceslcurves.cfm). In addition, park managers may benefit from consulting with local agencies, such as the Association of Bay Area Governments (ABAG) Resilience Program and the Bay Conservation Development Commission (BCDC) Adapting to Rising Tides Program, which are partnering to create a process that will support the development of climate adaptation plans.

Coastal Resource Management and Planning

The National Park Service has developed a variety of datasets and guidance for managing coastal resources and planning for the impacts of climate change. Refer to Appendix B for laws, regulations, and NPS policies pertaining to coastal resources.

The NPS *Coastal Adaptation Strategies Handbook* (Beavers et al. in review) will provide climate change adaptation guidance to coastal park managers in Golden Gate National Recreation Area, Fort Point National Historic Site, and the 116 other parks that have been identified by their regional offices as potentially vulnerable to sea level change. Focus topics include NPS policies relevant to climate change, guidance on evaluating appropriate adaptation actions, and adaptation opportunities for planning, incident response, cultural resources, natural resources, facilities and assets, and infrastructure. The handbook will also provide guidance on developing communication and education materials about climate change impacts, and it will detail case studies of the many ways that individual park managers are implementing adaptation strategies for threatened resources.

Additional reference manuals that guide coastal resource management include NPS Reference Manual #39-1: *Ocean and Coastal Park Jurisdiction*, which can provide insight for managers in parks with boundaries that may shift with changing shorelines. This manual is available at http://www.nps.gov/applications/npspolicy/DOrders.cfm. Also, NPS Reference Manual #39-2: *Beach Nourishment Guidance* (Dallas et al. 2012) is useful for planning and managing nourishment projects.

The NPS Geologic Resources Division can provide coastal resource management and planning assistance in the form of site specific investigations such as those by Eshleman (2012). Park managers should continue to submit technical assistance requests for these services.

The NPS Geologic Resources Division (GRD) and Climate Change Response Program (CCRP) are developing sea level rise and storm surge data that park managers can use for planning purposes over multiple time horizons. The project should be completed by 2016 and will analyze rates of sea level coupled with potential storm surge in 105 of the vulnerable parks in order to project, for each park, the combined elevations of storms surge and sea level by 2030, 2050, and 2100.

Dallas et al. (2013) published an inventory report about coastal engineering projects such as seawalls, dredge and fill projects (e.g., inlets), beach nourishment, and dune construction projects in the park. That inventory identified 116 coastal engineering projects in and adjacent to the park, 94 coastal structures spanning 26 km (16 mi), and 17 episodes of beach nourishment at eight beaches from 1872 to 2012. Dredge and fill projects and aggregate mining in the San Francisco Bay were shown to have played a major role in altering sediment supply and trends in the park (see "Coastal Erosion and Sediment Trends" section). The report also included historic data, imagery, cost, and a discussion of impacts (where available and appropriate). It accompanies a geographic information system (GIS) database and can be accessed at https://irma.nps.gov/DataStore/Reference/Profile/2194702.

Peek et al. (2015) assessed the risk of exposure of coastal assets in Golden Gate National Recreation Area and at Fort Point National Historic Site (see "Impacts of Sea Level Rise" section). Findings showed that 11% of the recreation area's assets and 29% of Fort Point's assets are considered "high exposure" to 1 m of sea level rise.

Pendleton et al. (2005) completed a coastal vulnerability index (CVI) assessment for the park. The CVI provided data for resource management and park facilities plans. CVIs use tidal range, wave height, coastal slope, shoreline change, geomorphology, and historical rate of relative sea level rise to create a relative measure of the coastal system's vulnerability to the effects of sea level rise. According to Pendleton et al. (2005), geomorphology, coastal slope, and wave height played the largest role in determining vulnerability of the shoreline while shoreline change, relative sea level rise, and tidal range were less of an influence. The assessment indicated that 50% of the park's shoreline is at high or very high risk of being impacted by sea level rise. Only 24% of the shoreline has low vulnerability (fig. 49; Pendleton et al. 2005). For more information about CVIs, refer to the US Geological Survey CVI website, http://woodshole.er.usgs.gov/project-pages/nps-cvi/. However, park staff found the results of the CVI to not accurately represent the park's overall coastal vulnerability because the methodology, which relies on the slope of the land above the shore, does not apply well to the Pacific Coast shoreline (Tamara Williams, Golden Gate National Recreation Area, hydrologist, personal communication, 13 October 2015).

The NPS Inventory and Monitoring (I & M) Program monitors rocky intertidal communities at three locations in the park; two are on the Marin Headlands and one is on Alcatraz Island (Weinberg 2013). Trends

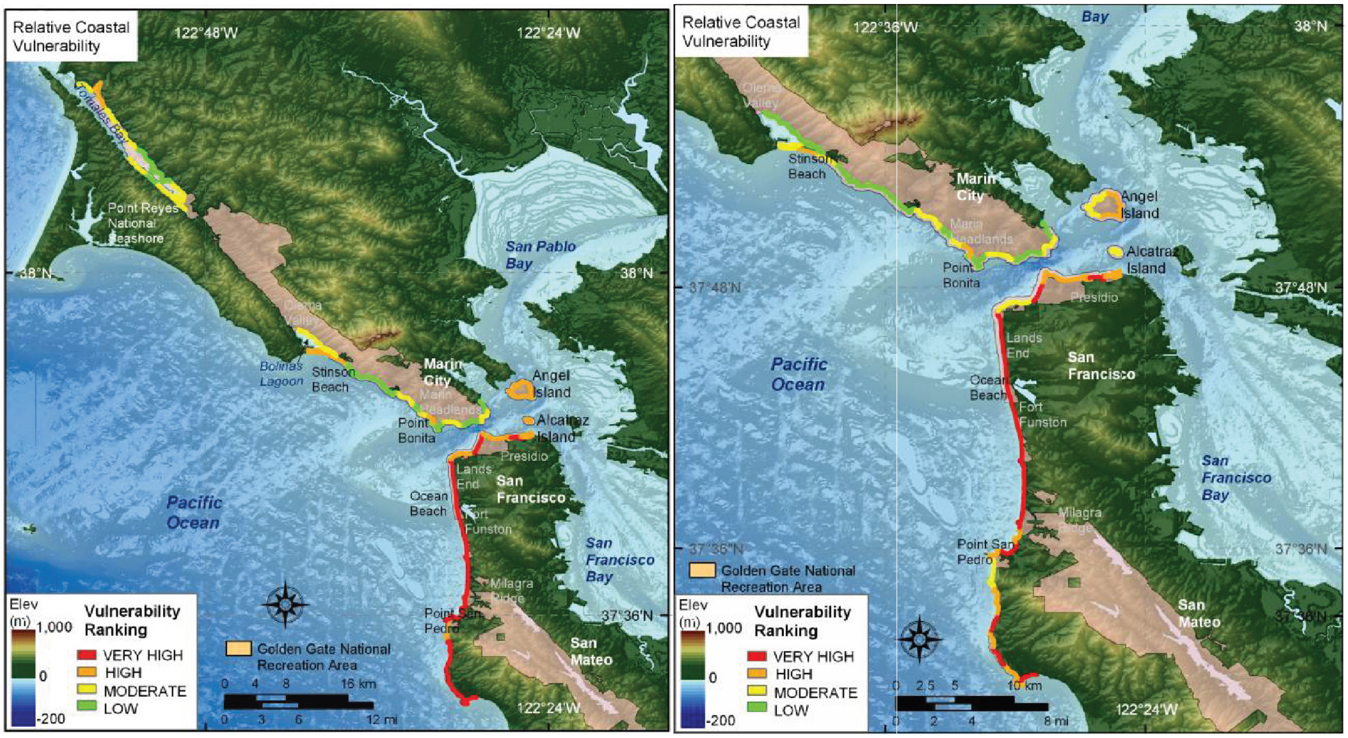


Figure 49. Coastal vulnerability maps. Investigators determined the relative coastal vulnerability index (CVI) of shorelines at Golden Gate National Recreation Area based on six variables: geomorphology, shoreline erosion/accretion rate, coastal slope, relative sea level rise rate, mean significant wave height, and mean tide range. The colored shorelines on the graphic represent these rankings from low (green) to very high (red). The map on the left includes Tomales Bay. The map on the right was recalculated without Tomales Bay. The methodology, however, does not apply well to the Pacific Coast shoreline and projected inundation maps may be a better resource until more accurate vulnerability maps are produced (Tamara Williams, Golden Gate National Recreation Area, hydrologist, personal communication, 13 October 2015). Maps from Pendleton et al. (2005, figures 11 and 13) available at http:/woodshole.er.usgs.gov/project-pages/nps-cvi/parks/GOGA.html.

have varied among the sites. The clearest trend shows rockweed and red algae at the Alcatraz site steadily rebounding after the impacts of a 2007 oil spill (Weinberg 2013). Additional information about rocky intertidal monitoring in the park is available at http://science.nature.nps.gov/im/units/sfan/monitor/rocky_intertidal.cfm.

Park staff members who are developing additional monitoring protocols can contact the San Francisco Bay Network for assistance, as well as consult suggested protocols such as the *Geological Monitoring* chapter about coastal features and processes. That chapter (Bush and Young 2009) described methods and vital signs for monitoring the following coastal features and processes: (1) shoreline change, (2) coastal dune geomorphology, (3) coastal vegetation cover, (4) topography/elevation, (5) composition of beach material, (6) wetland position/acreage, and (7) coastal wetland accretion.

The NPS Water Resources Division, Ocean and Coastal Resources Branch website (http://www.nature.nps.gov/water/oceancoastal) has additional information about servicewide programs and the resources and management programs at the ocean, coastal, and Great Lakes parks. Shoreline maps of coastal parks, along with shoreline and water acreage statistics from Curdts (2011) are available at http://nature.nps.gov/water/oceancoastal/shorelinemaps.cfm.

Coastal Erosion and Sediment Dynamics

Coastal erosion and sediment dynamics are primary concerns of park resource managers because these processes largely control the location and character of the shoreline, including beach width, cliff slope, shoreline orientation, and sediment composition, which in turn can impact visitor experience, park infrastructure, cultural resources, and other natural resources (Daphne Hatch, Golden Gate National

Recreation Area, chief of natural resources, conference call, 6 May 2014; Eshleman and Ward 2015). Coastal erosion in the area has damaged or removed coastal buildings, railroads, and roadways (Williams 2001). For example, erosion in the southern section of Ocean Beach has claimed portions of the north and south parking lots, has damaged the Great Highway, and currently threatens valuable wastewater infrastructure (Dallas et al. 2013; Eshleman and Ward 2015).

Coastal erosion, shoreline migration, and sediment deposition, however, are natural coastal processes and as such NPS policy generally requires that they be allowed to continue without interference (NPS *Management Policies 2006* § 4.8.1.1; Dallas et al. 2013; see Appendix B). NPS resource managers may intervene when no other feasible way is available to protect natural resources, park facilities, or historic properties (NPS *Management Policies 2006* § 4.8.1.1); or when human disturbance has altered these processes and NPS staff is working to restore the natural conditions to the area (Dallas et al. 2013). At the park, human activities have exacerbated coastal erosion and altered the sediment dynamics of the region both indirectly, as a result of the impacts of climate change, and directly, due to modifications to sediment input combined with coastal engineering projects (Dallas et al. 2013; Eshleman and Ward. 2015). For these reasons, NPS policy permits intervention.

In 2012, resource managers at the park requested technical assistance at Ocean Beach (figs. 50 and 51), Stinson Beach, Fort Funston, and Mori Point to address coastal processes. Geologic Resources Division and USGS Coastal and Marine Geology staff members collaborated on the development of a model to predict coastal hazards in the park and at Point Reyes National Seashore (Eshleman 2012).

Figure 50. Photograph of Ocean Beach. The southern end of Ocean Beach is severely eroding. Note the wide expanse of beach in the foreground in contrast to the narrow beach in the distance. View is to the south. National Park Service photograph by Kirke Wrench (Golden Gate National Recreation Area, date unknown).

Figure 51. Photographs of coastal engineering at Ocean Beach. An emergency rock revetment was installed following the 2009/2010 storm season which destroyed part of the road and guardrail near Ocean Beach. Top: Photograph shows rubble and sand. The rubble is from erosion of fill that was put in place during construction of the Great Highway. The sand originally accumulated by aeolian processes in the Ocean Beach parking lot and was removed sometime in late 2011 or early 2012 and dumped over the edge of the roadway. Bottom: Photograph shows the exposed rock covering the outfall on the beach in front of the revetment. National Park Service photographs by Jodi Eshleman (NPS Geologic Resources Division) in 2012.

Erosion at Ocean Beach (fig. 50) was the primary concern of resource managers during the 2012 site visit. Schupp et al. (2015) outlined a long-term management strategy for Ocean Beach. The southern portion of Ocean Beach had been eroding for decades (Hapke et al. 2006; Schupp et al. 2015); Ocean Beach is in the shadow of a large submerged sand bar (specifically, an ebb-tidal delta), which focuses incident waves on the beach (Eshleman et al. 2007). Between 2004 and 2010, areas eroded by as much as 5.3 m/yr (17.4 ft/yr) (Barnard et al. 2012). A combination of seawalls, artificial dunes, revetments, beach nourishment, and nearshore dredge placement was used to mitigate the erosion hazard (fig. 51; see "Coastal Engineering Projects"; Dallas et al. 2103). The Ocean Beach Master Plan (San Francisco Planning and Urban Research 2012) now recommends a managed retreat strategy that incorporates elements of relocation and a wide range of soft and hard coastal engineering techniques (Dallas et al. 2013; Schupp et al. 2015). The coastal processes at Ocean Beach have been extremely well studied and continue to be monitored by Patrick Barnard and others of the US Geological Survey (Tamara Williams, Golden Gate National Recreation Area, hydrologist, personal communication, 13 October 2015).

At Stinson Beach, issues included the relocating of leach fields, a periodically flooded parking lot, and dune erosion mitigation (fig. 52; Eshleman 2012). At Fort Funston, the main issue was visitor safety associated with bluff instability during installation of a new tunnel and outfall structure (fig. 53; Eshleman 2012). At Mori Point, park staff was concerned about coastal erosion and impacts of adjacent structures on recently acquired land and a trail system (Eshleman 2012).

Climate Change

Sea level rise and more frequent and intense winter storms associated with climate change will likely exacerbate coastal erosion within the park and result in flooding (Pendleton et al. 2005). Coastal evolution in response to sea level rise and storms is influenced by several conditions including geologic framework (underlying geology) and nearshore bathymetry, characteristics of coastal landforms, coastal and nearshore oceanographic processes (e.g., waves, currents, and ocean circulation), and sediment supply and transport (Williams 2013). The most vulnerable locations are low-lying areas, such as Crissy Field, and gently sloping open coast beaches that have high wave

Figure 52. Photographs of Stinson Beach. Left: Photograph shows where freshwater was leaching through the dunes and pooling on the beach (date unknown). Right: Photograph shows the flooded north parking lot in January 2010. National Park Service photographs.

Figure 53. Photographs of the Vista Grande Outfall at Fort Funston. The outfall is located on NPS property at Fort Funston. It is owned by Daly City. Left: Photograph shows the view of the outfall from the beach. Right: Photograph is the view from the clifftop. National Park Service photographs by Jodi Eshleman (NPS Geologic Resources Division) in 2012.

energy, such as Ocean Beach where shoreline erosion rates and wave energy are both high (Pendleton et al. 2005). The amount of sediment needed to maintain estuarine-coastal systems in their current form increases as sea level rises (Dallas and Barnard 2011).

Modifications to Coastal Sediment Supply

Human activities have dramatically reduced the amount of sediment in the San Francisco Bay coastal system by preventing new sediment from entering the system and removing sediment already in place. The amount of sediment reaching the San Francisco Bay coastal system from the Sacramento River has decreased by roughly 50% in the last 50 years (Wright and Schoellhamer 2004; Barnard et al. 2013). This is primarily a result of river damming, changes in upland land use (e.g., urban development, agriculture, and over-grazing), and elimination of tidal wetlands by development (Dallas and Barnard 2011; Schoellhamer 2011). Aggregate mining and dredging also remove sediment (Dallas et al. 2013). The National Park Service and US Army Corps of Engineers collaborate about sediment management related to dredging for ports and disposal of material (Daphne Hatch, conference call, 6 May 2014). Since 1931, dredging within the Main San Francisco Ship Channel has removed more than 40 million m^3 (53 million yd^3) of sediment (Dallas et al. 2013). In addition, aggregate mining within central San Francisco Bay and along Ocean Beach has removed more than 20 million m^3 (25 million yd^3) of sediment during 103 mining episodes from 1956 to 2008 (Dallas et al. 2013). Dallas et al. (2013) presented a complete history of sediment modifications to the San Francisco Bay coastal system by human activities.

Modifications to coastal sediment supply, such as those described above, have many impacts on coastal features and processes (Dallas and Barnard 2011). Reduction in sediment supply not only changes the amount of sediment available to build beaches, it can also affect the size and shape of offshore features such as deltas, which play an important role in dissipating wave energy (Dallas and Barnard 2011). Accelerated rates of shoreline erosion along open coast beaches correlate with a decrease in coastal sediment supply (Dallas and Barnard 2011).

The amount of sediment needed to maintain estuarine-coastal systems in their current form increases as sea level rises (Dallas and Barnard 2011). Thus, the current, human-induced sediment deficit in the San Francisco Bay coastal system is a concern for park managers. Management of the coastal system in the park requires consideration of "sediment transport pathways" and recognition of the "cumulative impacts of modifications to the sediment supply" (Dallas and Barnard 2011, p. 203).

Coastal Engineering Projects

Coastal structures can inhibit wave action to limit erosion in one area but they are generally expensive, intrude upon the viewshed, and come with unintended consequences. Structures may protect one stretch of coastline at the cost of another. For example, extensive rock revetments placed at Ocean Beach in 1998 and 2010 negatively impacted aesthetics, habitat value, and coastal processes (Eshleman and Ward 2015). Additionally, a breakwater installed near Half Moon Bay in 1960 successfully shielded the bay but altered wave patterns in the process (Williams 2001). Wave energy became focused on Granada Beach, causing erosion rates to increase from 2.5 cm (1 in) per year to more than 1 m (3 ft) per year (Mathieson et al. 1997). Therefore, Dallas et al. (2013) recommended the removal of all obsolete coastal structures within the park, where possible.

Alternative erosion control measures, such as sandbags have been used on Ocean Beach. Sandbags degrade quickly relative to rock and steel and are also not aesthetically pleasing. Park managers could work with San Francisco Public Utilities Commission to have the sand that accumulates in the Ocean Beach parking lot dumped over the bluff at the location of the sandbags. This would cover the sandbags, protecting them from degradation, and reduce the viewshed impact (Eshleman 2012).

Beach nourishment is another, albeit temporary, solution. It requires the availability of compatible sediment within a reasonable transport distance, however, and the sourcing of sufficiently large quantities of sand compatible with the eroding beach in terms of size and mineralogy can be difficult (Schupp 2015). Finer sands tend to wash away too quickly; coarser sands create artificial beach berms and impact nearshore habitats (Schupp 2015). Additionally, beach nourishment will impact coastal sediment dynamics (see previous section). At the time of this report, beach nourishment activities were not taking place at the park (Daphne Hatch, conference call, 6 May 2014).

Marine Features and Offshore Mapping

Golden Gate National Recreation Area contains 10,114 "water acres" consisting of ocean, estuarine, and intertidal areas (Curdts 2011). At the scoping meeting, participants recognized that the absence of a geologic map of the coastal and submerged portions of the park contributed greatly to the lack of knowledge about its marine resources (Kellerlynn 2008). The GRI GIS data do not include submerged geology. Such geologic maps are rare.

Submerged land in and near the park have been impacted significantly by human activities (see "Coastal Erosion and Sediment Dynamics" section); for example, between 1851 and 2011, dredge and fill projects disturbed more than 5.7 km^2 (1,400 ac) of submerged and subaerial land within and adjacent to the park. A geologic map that includes the submerged portion of the park could be used for resource management. Marine features that may be identified with the aid of such a map could include submerged bathymetric features (e.g., bed forms, channels, rocks, and shipwrecks), substrate, and reefs. In addition, a submerged geology map could aid in the understanding of local marine processes such as tides, currents, upwelling, and freshwater plumes.

Greene et al. (2009) compiled all available seafloor data into a marine benthic habitat map for Golden Gate National Recreation Area. In 2014–2015, the US Geological Survey's California Seafloor Mapping Program published a series of 1:24000-scale geologic maps that extend 5 km (3 mi) offshore and synthesize the subsurface geology in the San Francisco Bay Area (Sam Johnson, US Geological Survey, geologist, conference call, 6 May 2014). The US Geological Survey maps and GIS data are available at http://walrus.wr.usgs.gov/mapping/csmp/index.html.

If park managers are interested in developing monitoring protocols for marine features and processes, they can contact the San Francisco Bay Area Network, as well as consult the *Geological Monitoring* chapter about marine features and processes (Bush 2009), which described five methods and vital signs for monitoring: (1) the general setting of the environment, of which water depth is the primary indicator; (2) the energy of the environment, waves, and currents; (3) barriers, including reefs and other offshore barriers, which block energy; (4) seafloor composition or substrate; and (5) water column turbidity.

Sea Cave Documentation and Management

All caves in Golden Gate National Recreation Area are sea caves as described in the "Sea Caves" section. Cave features are nonrenewable resources. The Federal Cave Resources Protection Act of 1988 requires the identification of "significant caves" in NPS areas, the regulation or restriction of use as needed to protect cave resources, and inclusion of significant caves in land management planning. The act also imposes penalties for harming a cave or cave resources and exempts park managers from releasing specific location information for significant caves in response to a Freedom of Information Act (FOIA) request (see Appendix B of this report). These regulations also state that "no employee shall disclose information that could be used to determine the location of any significant cave unless the [superintendent] determines that disclosure will further the purposes of the act and will not create a substantial risk to cave resources of harm, theft, or destruction. All caves in parks are considered "significant," according to NPS policy.

A cave management plan has not yet been completed for the park. Such a plan would include a comprehensive cave inventory, an evaluation of current and potential visitor use and activities, and a plan to study known caves and discover new caves. The NPS Geologic Resources Division can facilitate the development of such a plan.

The *Geological Monitoring* chapter (Toomey 2009) about caves and associated landscapes may be a useful resource during development of a cave management plan. That chapter described methods for inventorying and monitoring cave-related vital signs, including the following: (1) cave meteorology, such as microclimate and air composition; (2) airborne sedimentation, including dust and lint; (3) direct visitor impacts, such as breakage of cave formations, trail use in caves, graffiti, and artificial cave lighting; (4) permanent or seasonal ice; (5) cave drip and pool water, including drip locations, rate, volume, and water chemistry, pool microbiology, and temperature; (6) cave microbiology; (7) stability issues associated with breakdown, rockfall, and partings; (8) mineral growth of speleothems, such as stalagmites and stalactites; (9) surface expressions and processes that link the surface and the cave environment, including springs, sinkholes, and cracks; (10) regional groundwater levels and quantity; and (11) fluvial processes, including underground streams and rivers. Additionally, Bunnell (1998) reported that the Golden Gate Grotto (caving group) performed sea cave surveys in Marin and San Mateo counties. Contacting this organization for more information may be beneficial for park planning.

Planning for a sea cave inventory is underway through cooperative efforts among park staff, the NPS Geologic Resources Division, and the local caving and kayaking community. Completion of the inventory must overcome a number of challenges, including cliffs and headland accessibility, worker safety, and limiting disturbance of wildlife. The inventory efforts follow the production of a sea cave inventory protocol and aerial reconnaissance maps by Garret and Williams (2008). The reconnaissance maps identified more than 500 potential sea caves along the coast of the park.

The sea cave inventory could record the size and orientation of each cave; document biota and habitat; and record recent, historic, and prehistoric human impacts (including trash, campsites, ship parts, and artifacts. The inventory will establish baseline data critical to documenting loss or damage of natural and cultural cave resources and habitat as a result of sea level rise (see "Sea Level Rise" section), pollution (e.g., litter, oil, and wastewater), and human access. The baseline data will also allow park managers to monitor changes in cave size, breakdown rate, substrate type, visitation (human and animal) and sea level (Garrett and Williams 2008). In addition, a sea cave inventory will allow park managers to identify and mitigate risks to wildlife and visitor safety.

Paleontological Resource Inventory, Monitoring, and Protection

Fossils within the park are significant and summarized in inventory reports by Elder et al. (2008), Henkel et al. (2015), and the "Paleontological Resources" section of this report. 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 Appendix B). Department of the Interior regulations associated with this act are under development. NPS policy-level guidance is provided in Management Policies 2006 (§ 4.8.2, 4.8.2.1).

In addition to the inventory reports, a variety of publications and resources provide park-specific or servicewide information and paleontological resource management guidance. Brunner et al. (2009) presented a summary of paleontological resource management challenges associated with coastal parks and suggested policy-based resource management considerations. 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. Henkel et al. (2015) provided a baseline inventory of fossil resources that may be used as the foundation for future monitoring plans.

Threats to paleontological resources in the park include unauthorized (non-permitted) collecting, vandalism, and erosion (Henkel et al. 2015). With increasing recreational use, there is increased potential for illegal fossil collecting within the park. As with all National Park Service areas, fossil collecting is prohibited in the park. However, this regulation may not be common knowledge for all visitors. Beachcombers are allowed to collect unoccupied modern shells along beaches in the park; however, in the process, they may inadvertently collect fossils, which is not permitted (National Park Service 2006). Brunner et al. (2009) provided policy guidance for this issue. Of particular concern is the collection of fossil sand dollars at Fort Funston (Will Elder, Golden Gate National Recreation Area, park ranger, conference call, 6 May 2014; Henkel et al. 2015). Vandalism and erosion of paleontological resources occur as a result of illegal encroachment activity such as short-cutting trails (Henkel et al. 2015). High erosion rates and landslides in the park warrant monitoring of paleontological resources where those processes are evident (Vincent Santucci, NPS Geologic Resources Division, geologist, conference call, 6 May 2014).

Elder et al. (2008) and Henkel et al. (2015) provided extensive and detailed lists of suggestions to better protect, document, and understand the park's fossil resources, and to share and expand paleontological knowledge. Their suggestions are listed here, grouped into four categories:

Education and Outreach-Related Suggestions

- Establish a stewardship program.
- Participate in National Fossil Day and the NPS Junior Paleontologist program.
- Develop and install fossil exhibits, including casts of museum specimens, for hands-on visitor use.
- Stabilize in situ fossils for display in the field.
- Establish a fossil collection for park interpreters to study.
- Increase public awareness of the values of fossils, NPS regulations, and how to differentiate between true fossils and modern remains of coastal organisms.
- Provide training for park staff to increase recognition of fossils in the field.
- Provide paleontological resource protection training for park staff (available through the NPS Geologic Resources Division).

Inventory-Related Suggestions

- Establish a field-based inventory program.
- Conduct an in depth field-based inventory (beyond the limited field-based inventory conducted by Henkel in 2012).
- Cooperate with local universities and use internship programs to perform field work.
- Document and archive interviews with notable scientists that have worked in the park.

- Develop and maintain a photographic archive of park fossils.

Monitoring and Protection–Related Suggestions

- Establish a field monitoring program.
- Use the inventory to create monitoring prescriptions.
- Patrol known fossil locations periodically, especially after storms, and more frequently in high-visitation areas.
- Determine if park fossils have a significant commercial value, which could be contributing to unauthorized collection.
- Encourage and support scientific research within the park.
- Submit technical assistance requests related to monitoring and protection of fossil resources to the NPS Geologic Resources Division through the STAR system.

Suggestions Related to Ongoing Park Activities

- Train park staff to look for, recognize, and report fossils they come across in the field (e.g., along bluffs, cliffs, or eroding gullies) as part of their regular duties.
- Incorporate paleontological resource protection into park planning.
- Use the Paleontological Sensitivity Map created by Henkel and Elder in 2014 to identify whether a paleontological resource evaluation needs to take place prior to park projects involving ground disturbance.
- Ensure that discoveries of late Pleistocene to Holocene fossils are reported to the park's archeologist.

Monitoring Aeolian Resources

Aeolian features in the park include dunes (see "Coastal Features and Processes" section). Dunes protect the shoreline from the impact of waves and storms and provide habitat for a variety of plants and animals. Dunes once covered the majority of San Francisco but have been largely removed by development. Monitoring remaining dune fields could help park managers determine trends in dune growth and identify areas that require protection.

Figure 54. Photograph of the dune field at Fort Funston. Today, the largest remaining dune field (dune sand, younger; Qdsy) is at Fort Funston. The lighter colored sediments underneath the dune sands belong to the Colma Formation (Qc). Photograph copyright © 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org, taken 25 September 2010, used with permission.

In the *Geological Monitoring* chapter about aeolian features and processes, Lancaster (2009) described the following methods and vital signs for monitoring aeolian resources: (1) frequency and magnitude of dust storms, (2) rate of dust deposition, (3) rate of sand transport, (4) wind erosion rate, (5) changes in total area occupied by sand dunes, (6) areas of stabilized and active dunes, (7) dune morphology and morphometry, (8) dune field sediment state (supply, availability, and mobility), (9) rates of dune migration, and (10) erosion and deposition patterns on dunes.

Based on aerial imagery, the only locations in the managed area of the park with dunes that could be monitored are Fort Funston (fig. 54), Ocean Beach, and Baker Beach. Though dune sands (**Qdsy**) do extend beyond these locations (fig. 35) they appear to be inactive and/or too dispersed for monitoring.

Geothermal Resource Protection

No known issues are associated with the hot spring near Steep Ravine Beach (Daphne Hatch, Golden Gate National Recreation Area, chief of natural resources, conference call, 6 May 2014; see "Geothermal Systems and Hydrothermal Features" section).

Should park managers desire more detailed information about the feature, the *Geological Monitoring* chapter about geothermal systems and hydrothermal features (Heasler et al. 2009) includes the following methods and vital signs for understanding geothermal systems and monitoring hydrothermal features: (1) thermal feature location, (2) thermal feature extent, (3) temperature and heat flow, (4) thermal water discharge, and (5) fluid chemistry.

Coastal Serpentine Scrub Preservation

Resource managers are very interested in the location of serpentinite outcrops and serpentine soils because rare and endemic vegetation is associated with them (see "Ecosystem Connections" section in the "Geologic Setting" chapter of this report). Park staff has made considerable effort in restoring coastal scrub habitat and locating serpentinite outcrops at the Presidio (Daphne Hatch, Golden Gate National Recreation Area, chief of natural resources, conference call, 6 May 2014). The GRI GIS data show the locations of serpentinized ultramafic rocks (**KJfsu**), which may be useful in identifying additional areas of serpentinite.

NPS Soil Resources Inventories have been completed for all three NPS units that are the subject of this report (National Park Service 2005a, 2005b, 2013) and may be useful for locating serpentine soils. More detailed geologic and soil maps could assist resource managers with coastal serpentine scrub preservation. The Geoscientists-in-the-Parks program is an option to support such projects (see http://go.nps.gov/gip).

Products associated with the NPS Vegetation Mapping Inventories are also available (National Park Service 2003); however, the vegetation map assigns coastal bluffs to the dunes category which is problematic for identifying coastal serpentine scrub communities (Daphne Hatch, conference call, 6 May 2014). Additionally, climate change will undoubtedly have an effect on vegetation distribution and is, therefore, a significant factor to consider in development of any preservation plans. NPS Inventory and Monitoring Program staff has begun monitoring plant communities in the park, with 2015 as the first year of formal monitoring. More information about plant community monitoring in the park is available at http://science.nature.nps.gov/im/units/sfan/monitor/plant_change.cfm.

Disturbed Land Restoration

Disturbed land restoration (DLR) is the process of restoring lands where the natural conditions and processes have been impacted by development (e.g., facilities, roads, mines, dams, or abandoned campgrounds) and/or by agricultural practices (e.g., farming, grazing, timber harvest, or abandoned irrigation ditches) to the unimpaired natural conditions. Many potential DLR projects exist within the park as a result of military activities, urban development, and past agricultural practices (O'Farrel 2007; Daphne Hatch, Golden Gate National Recreation Area, chief of natural resources, conference call, 6 May 2014).

DLR projects typically proceed as staff and budget allow; an exception is the Presidio, which park staff made a priority and have completed considerable restoration work (Daphne Hatch, conference call, 6 May 2014). For example, the Crissy Field area in the Presidio has experienced more changes in use than any other site in the park, and its restoration to a tidal marsh was a monumental effort (fig. 55; Presidio of San Francisco 2015b). Marsh restoration efforts such as the Crissy Field project are "important steps towards

Figure 55. Photographs of Crissy Field throughout restoration. (A) Before restoration, Crissy Field was a derelict parking lot with limited public access. (B) Restoration activities involved excavating the marsh. In 1999, the excavated marsh was reconnected to the San Francisco Bay. (C) Three years after restoration activities were completed, the area became a functional marsh habitat and recreation destination. (D) Today, the marsh ecosystem continues to thrive. National Park Service photographs.

restoring and protecting ecosystem health, and should continue to be designed with climate change impacts in mind" (Dallas et al. 2013, p. 54). The GRI GIS data include layers for "Historic Marsh Land and Tidal Flats" and "Historic Shoreline."

Several projects were in progress or recently completed at the time of writing this report. Restoration of a network of wetlands, a lagoon, and dunes is occurring in the Redwood Creek area of Muir Beach (fig. 56; see also https://www.nps.gov/goga/learn/nature/muir-beach.htm). Restoring the floodplain and hydrologic function to Redwood Creek at Muir Beach is of primary importance to resource managers. Muir Woods National Monument is part of the Muir Creek watershed. Excess fill is being used to restore a quarry to natural conditions on the Marin Headlands. Finally, the Tennessee Valley Reservoir Dam was recently designated a high hazard and will probably be removed within a few years (Daphne Hatch, conference call, 6 May 2014).

Previous involvement by the Geologic Resources Division with disturbed lands in the park included site-specific investigations by Harold Pranger and David Steensen in 2002 (Pranger et al. 2003). They evaluated and made the following recommendations for nine sites:

- Stabilize Marincello Road.
- Reclaim/stabilize Capehart Quarry.
- Restore Hollis Pond.
- Stabilize and remove waste at Baker Beach bluffs.

Figure 56. Photograph of restored lagoon at Muir Beach. Restoration of a network of wetlands, a lagoon, and dunes is ongoing in the Redwood Creek area of Muir Beach. National Park Service photograph by Kirke Wrench (Golden Gate National Recreation Area, date unknown).

- Address slumping, relocate, and restore Upper Fisherman's Trail.
- Deposit gravel on Oakwood Valley Trail.
- Enhance fishery of Lower Easkoot Creek.
- Enhance wetland near the South Stinson Beach picnic area.
- Remove and restore the Haypress Pond Site (completed in 2003).

Resource managers at the park are encouraged to submit technical assistance requests for addressing these recommendations or any new, pressing DLR issues. Additionally, resources manager may want to consider developing a comprehensive disturbed lands inventory and a systematic plan to restore those sites (Pranger et al. 2003).

Naturally Occurring Hazardous Materials

Asbestos occurs naturally in California in serpentinite (**KJfsu**) and along associated regional thrust faults (Clinkenbeard et al. 2002, 2012). Asbestos is a known carcinogen, and inhalation of asbestos may result in the development of lung cancer or mesothelioma. Health hazards may arise when activities that disturb asbestos-containing rocks and soil generate asbestos laden dust that may be inhaled. Schlocker (1974) and Pellettier (1962) reported four sites in the park—"Angel Island", "near Fort Baker", "west peak of Mt. Tamalpais", "Fort Point-Presidio area"—that contained asbestos minerals (table 5, fig. 57; see Van Gosen and Clinkenbeard 2011). Asbestos may also occur in areas of serpentinite (see "Serpentinite" section and poster, in pocket).

The California Geological Survey has prepared maps showing areas that have the potential to contain

Table 5. Summary of natural occurrences of asbestos.

Historic Site Name	Asbestiform mineral	Associated Minerals	Host Rock	References
Angel Island	chrysotile	• lizardite • antigorite	serpentinite	Schlocker (1974, p. 58–61)
near Fort Baker	crocidolite	not reported	chert	Pelletier (1962, p. 5)
west peak of Mt. Tamalpais	chrysotile	not reported	not reported	Pelletier (1962, p. 11)
Fort Point-Presidio area	chrysotile	• lizardite • chlorite • enstatite • pyroaurite • montmorillonite	serpentinite	Schlocker (1974, p. 58–61)

Source: compiled by Van Gosen and Clinkenbeard (2011)

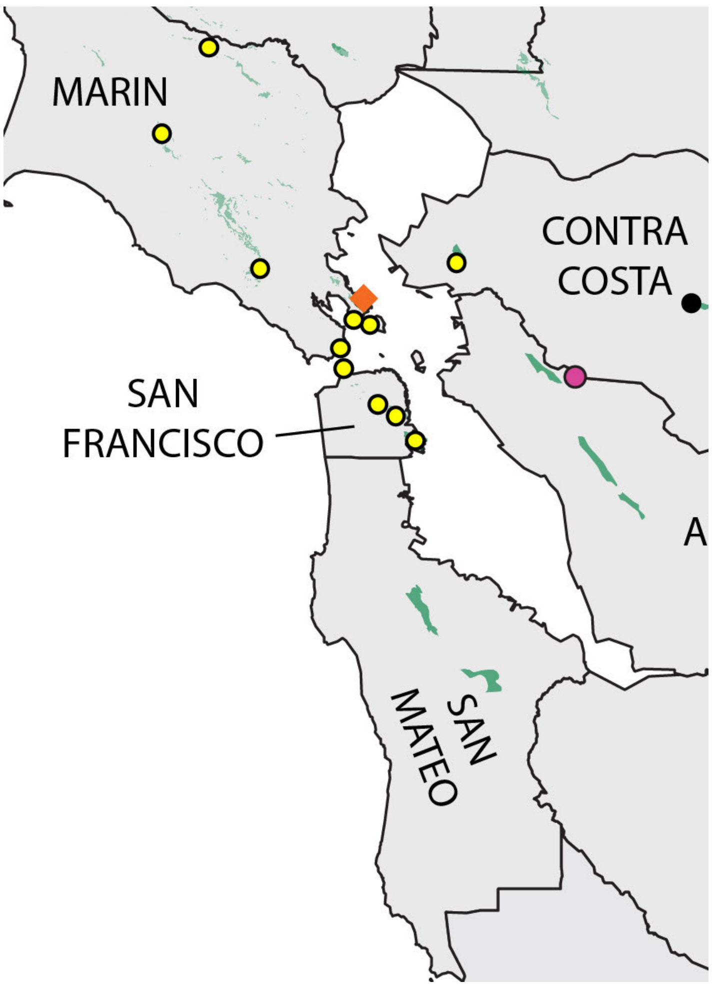


Figure 57. Map of asbestos locations in the San Francisco Bay Area. Four documented asbestos locations occur in the park. Yellow dots represent asbestos occurrences, pink dots are former asbestos mines, and orange diamonds represent reported fibrous amphibole locations. Green areas are ultramafic (serpentinite) rock outcrops. Graphic is a snapshot of a California Geological Survey Map Sheet (Van Gosen and Clinkenbeard 2011).

naturally occurring asbestos (Clinkenbeard et al. 2012). These maps are designed to be used by non-geologists, primarily planning departments and other decision-making agencies (Clinkenbeard et al. 2012; Wills 2012). The maps cannot be used to verify the actual presence of asbestos at a particular site, which would require a site-specific investigation, but they can be used to help agencies determine the potential extent of asbestos hazards (Clinkenbeard et al. 2012; Wills 2012). The maps and more information are available from the California Geological Survey at http://www.conservation.ca.gov/cgs/minerals/hazardous_minerals/asbestos/Pages/Index.aspx.

Although mercury is not known to affect park resources, it does occur in silica carbonate rocks (**KJfbsc**; see poster in pocket) as the naturally occurring mineral cinnabar (HgS). In the New Almaden Mining District in southwestern San Jose, silica carbonate rocks are the host for most of the cinnabar mined there (Crittenden 1951; Stoffer 2002). Mercury becomes a health hazard to animals and humans when it enters the food chain. This occurs most readily where mining and prospecting activities have concentrated mercury ore. Thus, knowing the locations of mines and prospects is important for resource management (see "Abandoned Mineral Lands" section; Clinkenbeard et al. 2012). Additionally, mercury from historic mercury mines or gold mines has entered a number of watersheds in California (Alpers and Hunerlach 2000). More information is available from the California Geological Survey at http://www.conservation.ca.gov/cgs/minerals/hazardous_minerals/mercury/Pages/index.aspx.

Groundwater Contamination

Contamination of groundwater by introduction of pollution from the surface is a major problem in the San Francisco Bay Area (Howard 1997). Soil and groundwater contamination in the park is largely related to past military land uses. Porosity and permeability of materials determine susceptibility to rapid pollution. Pollutants tend to follow high-porosity Holocene stream channel and levee deposits (**Qsc**, **Qafy**, **Qaly**, **Qalo**) (Helley 1986). Resource managers could use the GRI GIS data to locate these deposits in the park. Aging septic systems is another issue with respect to surface water quality, though these issues are beyond the scope of this report. Park managers are encouraged to contact the NPS Water Resources Division for assistance.

Abandoned Mineral Lands

According to the NPS Abandoned Mineral Lands (AML) database and Burghardt et al. (2014), the park contains 23 AML features at five sites (as of the completion of the servicewide AML inventory on 31 December 2013). Sites include sand and gravel quarries, copper mines, and a building stone (sandstone) quarry. Features include surface mines, adits, structures, waste rock, equipment, a prospect, and a shaft. Some of the AML features are culturally significant, such as the limestone quarry near Mori Point that was mined by the Spanish in the 1700s to supply whitewash for Presidio buildings. According to the GRI GIS source maps, 13 quarries and two borrow pits operated within the authorized boundary of the park, all of which are now abandoned. The AML database and GRI GIS data likely overlap.

Hydraulic gold mining activities occurred in the area during the late 19th century, releasing nearly 850 million m^3 (1.1 billion yd^3) of sediment into the San Francisco Bay coastal system (Dallas et al. 2013). Between 1953 and 2008, aggregate mining within central San Francisco Bay and on Ocean Beach removed more than 19 million m^3 (24 million yd^3) of sediment (see “Coastal Erosion and Sediment Dynamics” section; Dallas et al. 2013). Mercury was mined historically in California and widely used for gold recovery until about 1970 (Alpers and Hunerlach 2000). Asbestos has been mined in Central California, but no abandoned asbestos mines or prospects exist in the park (Van Gosen and Clinkenbeard 2011). Both mercury and asbestos may be hazardous to human health and the environment (see “Naturally Occurring Hazardous Materials” section).

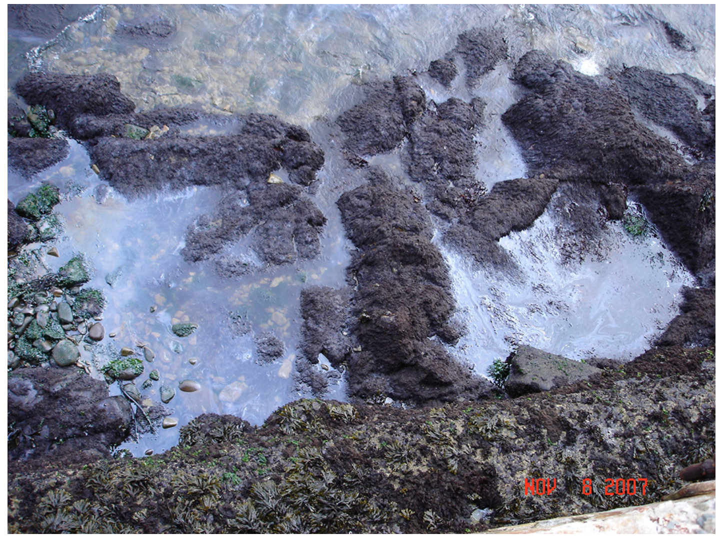


Figure 58. Photograph of oil pools on Alcatraz Island. Oil accumulated around Alcatraz Island following a spill in the main shipping channel of the San Francisco Bay. The oil spill devastated the tide-pool ecosystems that surround the island. National Park Service photograph taken in November 2007.

AML features present a variety of resource management issues such as visitor and staff safety and environmental quality of air, water, and soil. AML features can also provide habitat for bats and other animals. Resource management of AML features requires an accurate inventory and reporting, so all AML features should be recorded in the AML database. The NPS Geologic Resources Division can provide assistance. An accurate inventory helps identify human safety hazards and facilitates closures, reclamation, and restoration of AML features. When appropriate for resource management and visitor safety, AML features can also present opportunities for interpretation as cultural resources. Three AML features in the park had been mitigated and no others were in need of mitigation (Burghardt et al. 2014). Reclamation of the Capehart Quarry is addressed in the “Disturbed Lands Restoration” section. The NPS AML website, http://go.nps.gov/aml, provides further information.

External Energy and Mineral Development

The National Park Service works with adjacent land managers and other permitting entities to help ensure that National Park System 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, http://go.nps.gov/grd_energyminerals, provides additional information.

Aggregate mining began in San Francisco Bay in the 1930s and still occurs today in designated lease areas; some of these extend into the park's boundary (Dallas et al. 2013). Mining and dredging in the bay has reduced the sand supply to Ocean Beach and contributed to persistent beach erosion (Schupp et al. 2015; see "Coastal Erosion and Sediment Dynamics" section). According to Dallas et al. (2013, p.55), "park managers should work with the San Francisco Bay Conservation and Development Commission, and other agencies involved with aggregate mining, to communicate about mining activities located adjacent to park property."

As of 2006, known significant petroleum resources do not exist in the San Francisco Bay region (Stoffer 2006). Although oil is not extracted within or adjacent to park boundaries, the parks are in proximity of a major shipping channel through both the San Francisco Bay and along the Pacific Coast. Oils spills from ships transporting oil may therefore impact the shoreline of the parks. The most recent significant spill occurred November 2007. During that spill, 220,000 L (58,000 gal) of oil impacted the bay, killing and injuring wildlife and devastating tide-pool ecosystems (fig. 58).

Renewable Energy Development

Generation and transmission of renewable energy includes utility-scale solar, wind, geothermal, off-shore wind technologies, and hydroelectricity. The National Park Service uses a combined technical and policy approach to manage and protect park resources and values as renewable energy resources are identified and developed near NPS areas. Park resources and values that may be impacted by renewable energy development include water quantity and quality, air quality, wildlife, dark night skies, natural soundscapes, cultural resources, scenic views, soils, geologic and hydrologic processes, and visitor experience. The NPS Geologic Resources Division Renewable Energy website, http://go.nps.gov/grd_renewable, provides more information.

Park managers submitted several requests between 2012 and 2014 for technical, legal, and policy guidance related to proposed alternative energy projects in waters in and near the park. Park managers are concerned about the impacts of proposed tidal, wind, and wave energy projects on the park environment. The NPS Pacific West Regional Office has been working with park staff to review and comment on alternative energy proposals.

Development of wave, wind, and tidal energy resources has unknown impacts but could possibly affect sediment transport, aeolian processes, viewsheds, habitats and biological resources, underwater sea waves, and cultural landscapes.

Geologic History

This chapter describes the chronology of geologic events that formed the present landscape of Golden Gate National Recreation Area, including Fort Point National Historic Site and Muir Woods National Monument.

Assembling California

Five hundred million years ago the landmass of California had not yet formed. The area now occupied by the park was amid an ancient ocean and far to the west of a passive boundary similar to the East Coast of North America today. By 443 million years ago, the end of the Ordovician Period, the boundary had evolved from passive to active as an oceanic plate converged with the continent. As plate convergence occurred (throughout the Paleozoic Era), rocks accreted to the continent, some of which are now mapped in Yosemite National Park (see GRI report about Yosemite National Park by Graham 2012). The collision also caused mountain building in Nevada and Idaho and the uplifting of the Ancestral Rocky Mountains. These events mark the beginning of the assembly of California.

Franciscan Foundation

The Franciscan Complex forms the basement foundation under most of the park. By 200 million years ago (beginning of the Jurassic Period), the California landmass had grown and relative sea level had dropped, but the land that would become the park still had not assembled. The shoreline of western North America was near where the Sierra Nevada foothills are now, that is, approximately 160 km (100 mi) east of the modern shoreline.

By this same time (roughly 200 million years ago), however, the basalt and greenstone rocks that would eventually become part of the Franciscan Complex were beginning to form thousands of miles away at a mid-ocean ridge near the equator. They formed along an ocean floor that was moving as part of a tectonic plate toward California. As the basalt and greenstone were being transported, chert and limestone—also future Franciscan rocks—were deposited atop them. Nearly 150 million years would pass before some of these rocks reached the subduction zone. Upon their approach, graywacke sandstone and shale deposited by turbidity currents capped off the Franciscan accretionary wedge sequence, which is visible today in the park.

This subduction zone, which was off California during the Mesozoic Era, is referred to as the "Franciscan Subduction Zone"; the subducting oceanic plate is referred to as the "Farallon plate." From about 160 million to 50 million years ago (into the Cenozoic Era) the terranes of the Franciscan Complex periodically accreted onto the western edge of the North American continent (Wentworth et al. 1984; Wakabayashi and Unruh 1995). Additional details are presented in the "Geologic Setting and Significance" and "Geologic Features and Processes" chapters of this report.

Toward the end of Franciscan subduction (66–56 million years ago; Paleocene Epoch) north–south compression increased (Bartow 1991) and the Franciscan accretionary wedge was first unroofed (brought to the surface and exposed to erosion) as evidenced by weathered Franciscan material in Paleocene strata (Elder 2013; Bartow 1985). Most of the Paleocene rocks in the region (**Tw**, **Tb**, **Tsu**, and **Tsl**) are turbidites composed of weathered Franciscan material deposited on top of Salinian or Franciscan basement rocks in deep water.

Development of the San Andreas Fault System

The San Andreas Fault represents a transform plate boundary between the Pacific and North American plates. The transform fault replaced the ancient convergent boundary wherever subduction fully consumed the intermediate Farallon plate (see "San Andreas Fault System" section). Complete subduction of the Farallon plate first occurred near modern-day Los Angeles about 28 million years ago; this is where the San Andreas Fault originated (Atwater 1970, 1989; Page and Wahrhaftig 1989). The Pacific plate on the other side of the Farallon plate was moving northwest; therefore, when it came together with the North American plate, relative plate motion changed from plates colliding (convergent) to plates sliding past each other (transform) (fig. 59).

The site where the San Andreas Fault originated became known as the Mendocino triple junction

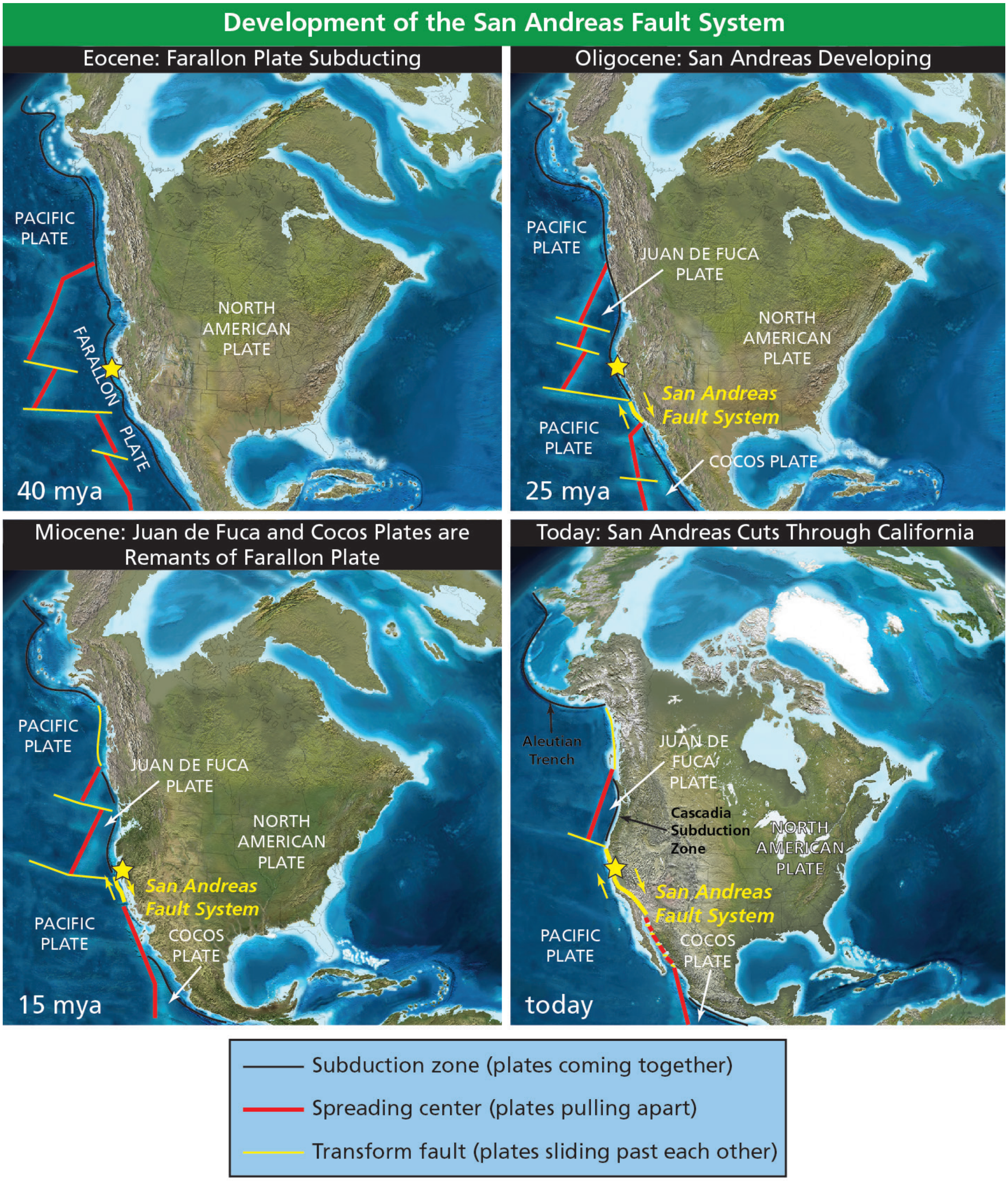


Figure 59. Paleogeographic maps of the growth of the San Andreas Fault system. When the spreading center between the Pacific and Farallon plates intersected the North American plate, a transform fault (San Andreas Fault system) formed, causing strike-slip (transpressional) movement. The Farallon plate has been subdivided into the Juan de Fuca plate, to the north, and the Cocos plate, to the south. Yellow stars indicate the approximate location of the park. "mya" = million years ago. Base paleogeographic maps by Ron Blakey (Colorado Plateau Geosystems, Inc.), available at http://cpgeosystems.com/paleomaps.html. Annotation by the author and Jason Kenworthy (NPS Geologic Resources Division).

because it is the point where three tectonic plates intersect. As plate motions continued over the next 18 million years (Tertiary Period), the Mendocino triple junction migrated northward and the San Andreas Fault lengthened in its wake. The transition from subduction to transform plate motion took millions of years. The San Andreas Fault reached the San Francisco Bay Area roughly 10 million years ago (Page and Wahrhaftig 1989). Subduction continues today to the north, off the coast of Oregon and Washington, and along the Aleutian Islands in Alaska (fig. 59). The San Andreas Fault has offset many Tertiary deposits and features (e.g., basins and uplifts), making paleogeographic reconstructions for specific time periods very difficult (Elder 2013).

The northward migration of the Mendocino triple junction was also accompanied by volcanism; a trailing gap in the crust allowed mantle material to well up to the surface. Stanley et al. (2000) hypothesized that intense volcanic activity occurred episodically. The result in the area of the park was a series of volcanic rocks that range in age from 15 million to 3 million years old and get younger to the north (Turner 1970; Pampeyan 1993; Wagner et al. 2011). Though these rocks do not occur in the park, they are significant because they form the basis for the soil used to cultivate wine grapes in the Sonoma and Napa valleys.

Hydrothermal activity related to this volcanism altered much of the serpentinite, especially along shear zones, to silica-carbonate minerals. It also emplaced mercury ore deposits (cinnabar) within the newly formed silica-carbonate rocks (**KJfbsc**) (see "Hydrothermal Areas" section; Schlocker et al. 1958; Bailey et al. 1964; Pampeyan 1994; Blake et al. 2000; Stoffer 2002).

Evolution of the Modern Landscape

The San Andreas Fault has been displacing rocks and deposits in the Bay Area for the last 10 million years. The oldest offset rocks are those of the Salinian Complex which traveled all the way from Southern California to their current locations at Montara Mountain and Pointe Reyes. Their counterparts on the other side of the fault are far beyond the map. Both sides of more recent formations such as the Santa Clara (**QTsc**) and Merced (**QTm**) are visible on the map, however. Both formations are displaced to the northwest on the west side of the San Andreas Fault as a result of transform movement.

A slight component of compression between the Pacific and North American plates began at least 3.5 million years ago, possibly even several million years earlier (Sloan 2006). The combination of transform movement and compression is called transpression (fig. 2). Uplift and subsidence is a result of transpression and responsible for creating the hilly landscape characteristic of the area today.

The modern California Coast Ranges, the Santa Cruz Mountains, and the Diablo Range started to uplift at least 3.5 million years ago, but possibly even several million years earlier (Page 1989; Sloan 2006). At the same time, the region now occupied by the San Francisco Bay began to subside, flooding the coastal embayment with marine waters (Stoffer 2002, Sloan 2006). Both uplift and subsidence continue to occur today, though the rate of uplift far exceeds the rate of subsidence (Brown 1990). Uplift rates around 10,000 years ago (late Pleistocene Epoch) at Fort Funston were between 0.4 to 0.5 mm (roughly 1/50 in) per year (Kennedy 2005). While San Francisco Bay is stable or slowly subsiding (Page 1989), remnants of hills which formed in only the last few million years by uplift protrude from the bay as islands such as Alcatraz and Angel islands.

A series of ice ages (glacial cycles) began approximately 1.8 million years ago and ended about 10,000 years ago (Stoffer 2002). Sea level change during each cycle of glaciation was in the range of 50 to 150 m (160 to 500 ft) (Stoffer 2002). During glacial (cold) periods, when sea level was low, the ancestral Sacramento River eroded and downcut through the bay floor; during interglacial (warm) periods, marine waters flooded into the bay (Elder 2001). Cores taken from San Francisco Bay during bridge-foundation studies recorded as many as seven interglacial periods (indicated by estuarine rocks which correspond to times of high sea level) over the last 500,000 years (Atwater et al. 1977; Sloan 1989).

In the park, the Merced Formation (**QTm**), which formed in a basin alongside the San Andreas Fault, preserves evidence of at least nine glacial cycles in the past 600,000 years (Stoffer 2002). A change from local Franciscan source sediments to Sierran source sediments at about 600,000 years ago in the Merced Formation indicates the start of the modern Sacramento River drainage system (Elder 2013). Prior to this time, the Sacramento River emptied into a large, land-locked

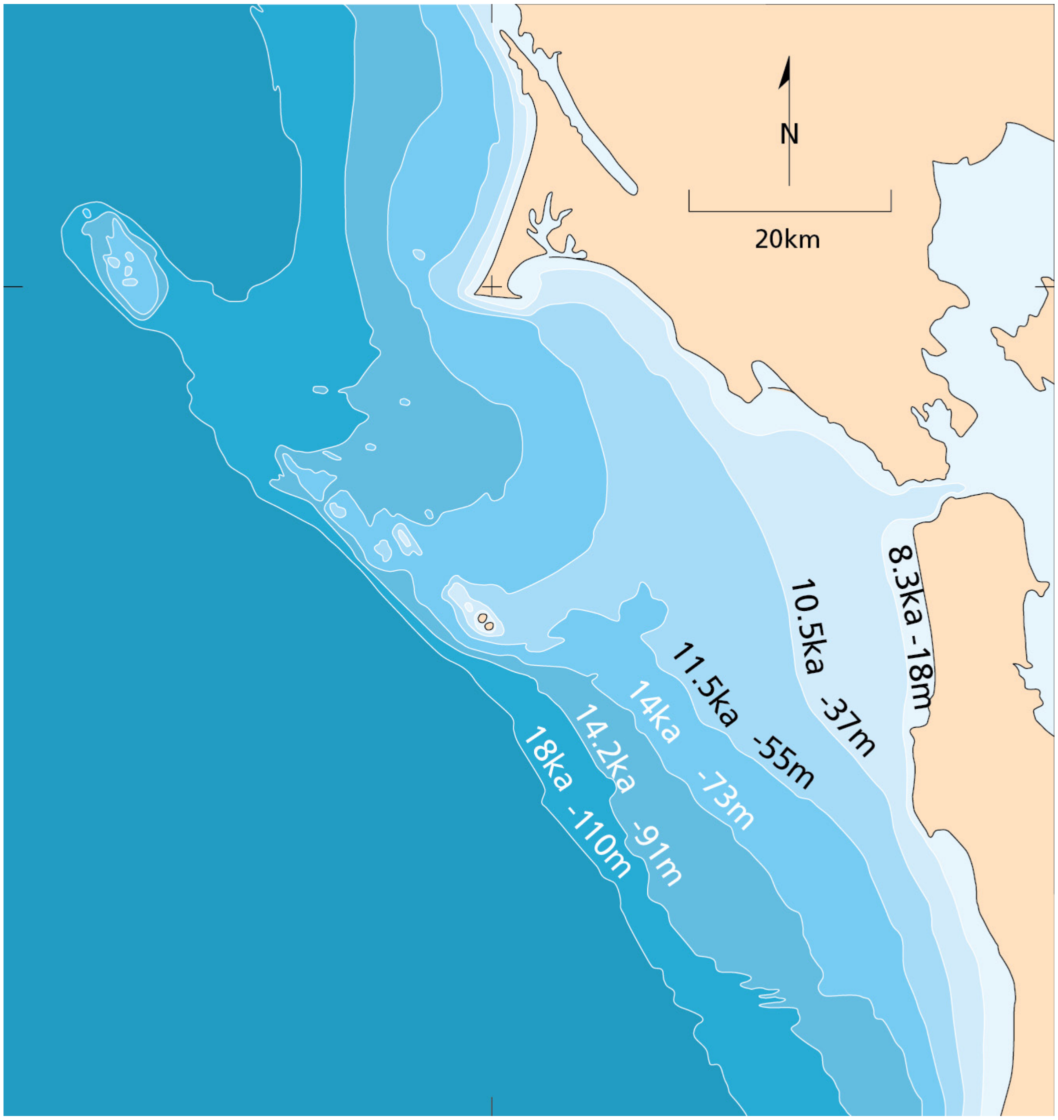


Figure 60. Map of sea level fluctuations. Since the last major global glaciation, which ended about 20,000 years ago, sea level has risen. A particularly long standstill occurred about 11,500 years ago (as indicated by a thick, widespread accumulation of nearshore gravel and sand). Afterward, sea level again began to rise. US Geological Survey map by K. R. Lajoie after Anderson et al. (2001, fig. 4.6).

lake in the Central Valley (Hall 1965; Sarna-Wojcicki et al. 1985; Elder 2013).

During the most recent glacial maximum (called the "Wisconsinan") about 20,000 years ago, sea level was as much as 130 m (430 ft) lower than it is today and the coastline was about 35 km (22 mi) to the west (fig. 60; Anderson et al. 2001). San Francisco Bay was a forested valley, and the Farallon islands were hills (rather than islands) above a broad coastal plain (Anderson et al. 2001). Toward the end of this most recent ice age, sea level began to rise and the sand dunes, which once covered San Francisco, were deposited (see "Coastal Features and Processes" section; Schlocker et al. 1958; Atwater 1979; Sloan 1989). Sand from the broad coastal plain was blown over the coastal hills between about 18,000 and 5,000 years ago (Atwater 1979). By about 9,000–8,000 years ago, sea level rose high enough to flood the Sacramento River Valley, creating the San Francisco Bay (Atwater et al. 1977; Elder 2001). By about 5,000 years ago, sea level had nearly reached its current position (Anderson et al. 2001; Gehrels 2009); it continues to rise today (see "Sea Level Rise" section). Humans have long modified, and continue to modify, the landscape of the Bay Area, including efforts to restore disturbed landscapes.

Geologic Map Data

This chapter summarizes the geologic map data available for Golden Gate National Recreation Area, including Fort Point National Historic Site and Muir Woods National Monument. Posters (in pocket) display the map data draped over imagery of the parks and surrounding area. The Map Unit Properties Table (in pocket) summarizes this report's content for each geologic map within in the park. Complete GIS data are available at the GRI publications website, http://go.nps.gov/gripubs.

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, these maps portray the spatial distribution and temporal relationships of rocks and unconsolidated deposits. The American Geosciences Institute website, http://www.americangeosciences.org/environment/publications/mapping, provides more information about geologic maps and their uses.

Source Maps

The GRI team digitizes paper maps and converts digital data to conform to the GRI GIS data model. The GRI GIS data include essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, cross sections, figures, and references. The GRI team used the following sources to produce the GRI GIS data for the park. These sources also provided information for this report.

Blake, M. C., R. W. Graymer, D. L. Jones, and A. Soule. 2000. Geologic map and map database of parts of Marin, San Francisco, Alameda, Contra Costa, and Sonoma counties, California (scale 1:75,000). Miscellaneous Field Studies Map MF-2337. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/mf2337.

Bonilla, M. G. 1998. Preliminary geologic map of the San Francisco South 7.5' quadrangle and part of the Hunters Point 7.5' quadrangle, San Francisco Bay Area, California: a digital database (scale 1:24,000). Open-File Report OFR-98-354. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/ofr98354.

Brabb, E. E., R. W. Graymer, and D. L. Jones. 2000. Geologic map and map database of the Palo Alto 30' × 60' quadrangle, California (scale 1:100,000). Miscellaneous Field Studies Map MF-2332. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/mf2332.

Clark, J. C., and E. E. Brabb. 1997. Geology of Point Reyes National Seashore and vicinity, California: a digital database (scale 1:48,000). Open File Report OFR-97-456. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/ofr97456.

Pampeyan, E. H. 1994. Geologic map of the Montara Mountain and San Mateo 7.5' quadrangles, San Mateo County, California (scale 1:24,000). Miscellaneous Investigations Series Map I-2390. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/i2390

Schlocker, J., M. G. Bonilla, and D. H. Radbruch. 1958. Geology of the San Francisco North quadrangle, California (scale 1:24,000). Miscellaneous Geologic Investigations Map I-272. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/i272

Wagner, D. L., C. I. Gutierrez, and K. B. Clahan. 2006. Geologic map of the south half of the Napa 30'x60' quadrangle, California (scale 1:100,000). Preliminary Geologic Maps. California Geological Survey, Sacramento, California.

GRI GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is available at http://go.nps.gov/gridatamodel. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for the park using data model version 2.1. The GRI Geologic Maps website, http://go.nps.gov/geomaps, provides more information about GRI map products.

GRI GIS data are publically available through the NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/App/Portal/Home). Enter "GRI" as the search text and select a park from the unit list.

The following components are part of the GRI GIS data:

- a GIS readme file (goga_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information;
- data in ESRI geodatabase GIS format;
- layer files with feature symbology (table 6);

- Federal Geographic Data Committee (FGDC)–compliant metadata;
- an ancillary map information document (goga_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures; and
- an ESRI map document (goga_geology.mxd) that displays the GRI GIS data.

GRI Posters

The posters (in pocket) display the GRI digital geologic data draped over a shaded relief image of the parks and surrounding area. Not all GIS feature classes are included on the posters (table 6). Geographic information and selected park features have been added to the posters. Digital elevation data and added geographic information are not included in the GRI GIS data, but are available online from a variety of sources. Contact the GRI team for assistance locating these data.

Map Unit Properties Table

The Map Unit Properties Table lists the geologic time division, symbol, and a simplified description for each of the GRI GIS map units within the park. Following the structure of the report, the table summarizes the geologic features, processes, resource management issues, and history associated with each map unit.

Use Constraints

Graphic and written information provided in this report is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Please contact GRI with any questions.

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features in the GRI GIS data and on the posters. Based on the source maps scales (ranging from 1:24,000 to 1:100,000) and US National Map Accuracy Standards, geologic features represented in the geologic map data are expected to be horizontally within 12 m (40 ft) to 51 m (167 ft) of their true locations.

Table 6. GRI GIS data for Golden Gate National Recreation Area, including Fort Point National Historic Site and Muir Woods National Monument.

Data Layer	On GRI Posters?
Geologic Contacts	No
Geologic Units	Yes
Geologic Cross Section Lines	No
Geologic Attitude Observation Localities	No
Geologic Observation Localities	No
Mine Point Features	No
Hazard Point Features	No
Geologic Point Features	No
Geologic Line Features	No
Hazard Feature Lines	No
Fault and Fold Symbology	Yes
Folds	Yes
Faults	Yes
Alteration and Metamorphic Area Boundaries	No
Alteration and Metamorphic Areas	No
Historic Shoreline	No
Historic Marsh Land and Tidal Flats Boundaries	No
Historic Marsh Land and Tidal Flats	No
Mélange Blocks	No

Glossary

These are brief definitions of selected geologic terms relevant to this report. Definitions are based on those in the American Geosciences Institute Glossary of Geology *(5th edition; 2005). Additional terms are defined at http://geomaps.wr.usgs.gov/parks/misc/glossarya.html.*

accretion (structural geology). The addition of island-arc or continental material to a continent via collision, welding, or suturing at a convergent plate boundary.

accretionary wedge. See accretionary prism.

active margin. A tectonically active plate boundary where lithospheric plates are converging, diverging, or sliding past one another.

adit. A horizontal passage into a mine from the surface.

aeolian. Describes materials formed, eroded, or deposited by or related to the action of wind.

alluvial fan. A low, relatively flat to gently sloping, fan-shaped mass of loose rock material deposited by a stream, especially in a semiarid region, where a stream issues from a canyon onto a plain or broad valley floor.

alluvium. Stream-deposited sediment.

ammonite. Any ammonoid belonging to the suborder Ammonitina, characterized by a thick, ornamental shell with sutures having finely divided lobes and saddles. Range: Jurassic to Cretaceous.

amphibole. A group of silicate (silicon + oxygen) minerals composed of hydrous calcium and magnesium with the general formula $(Ca_2Mg_5)Si_8O_{22}(OH)_2$.

angular unconformity. An unconformity between two groups of rocks whose bedding planes are not parallel or in which the older, underlying rocks dip at a different angle (usually steeper) than the younger, overlying strata.

anticline. A fold, generally convex upward ("A"-shaped) whose core contains the stratigraphically older rocks.

aquifer. A rock or sedimentary unit that is sufficiently porous to hold water, sufficiently permeable to allow water to move through it, and saturated to some level.

arenite. A general term for sedimentary rocks composed of sand-sized fragments.

argillite. A weakly metamorphosed rock, derived from mudstone or shale, but more highly indurated; lacks the fissility of shale and the cleavage of slate.

ash. Fine-grained material, less than 2 mm (0.08 in) across, ejected from a volcano.

basalt. A volcanic rock that is characteristically dark in color (gray to black), contains approximately 53% silica or less, and is rich in iron and magnesium.

basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie rocks exposed at the surface, commonly sedimentary. In many regions the basement is of Precambrian age, but it may be much younger. Also, Earth's crust below sedimentary deposits that extends down to the Mohorovicic discontinuity.

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

batholith. A large, generally discordant plutonic body having an aerial extent of 40 mi^2 (100 km^2) or more and no known floor.

bathymetry. The measurement of ocean or lake depths and the charting of the topography of the ocean or lake floor.

bedding. Depositional layering or stratification of sediments.

bedrock. Solid rock that underlies unconsolidated sedimentary deposits and soil.

block (fault). A crustal unit bounded completely or partially by faults.

bivalve. Having a shell composed of two distinct, but equal or nearly equal, movable valves, which open and shut.

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

carbonate. A mineral group composed of carbon and oxygen plus an element or elements; for example calcite, $CaCO_3$; and dolomite, $CaMg(CO_3)_2$.

chalcedony. A cryptocrystalline variety of quartz.

chemical weathering. Chemical breakdown of minerals at Earth's surface via reaction with water, air, or dissolved substances; commonly results in a change in chemical composition providing more stability in the current environment.

chert. An extremely hard sedimentary rock with conchoidal fracturing, consisting mostly of interlocking crystals of quartz.

chronology. The arrangement of events in their proper sequence in time.

clastic. Describes rocks or sediments made of fragments of preexisting rocks.

clay. Minerals and sedimentary fragments that are less than 1/256 mm (0.00015 in) across.

colluvium. A loose, heterogeneous, and incoherent mass of rock fragments and soil material deposited via surface runoff or slow continuous downslope creep; usually collects at the base of a slope or hillside, but includes loose material covering hillsides.

compaction. The process whereby fine-grained sediment is converted to consolidated rock.

concretion. A hard, compact aggregate of mineral matter, rounded to irregularly shaped; composition generally differs from that of the rock in which it occurs.

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

contact. The surface between two types or ages of rocks.

continental crust. Earth's crust that is rich in silica and aluminum and underlies the continents and the continental shelves; ranges in thickness from about 25 km (15 mi) to more than 70 km (40 mi) under mountain ranges, averaging about 40 km (25 km) thick.

continental rise. Gently sloping region from the foot of the continental slope to the deep ocean abyssal plain; generally consists of smooth topography but may have submarine canyons.

continental shelf. The shallowly submerged—covered by water depths of less than 200 m (660 ft)—part of a continental margin that extends from the shoreline to the continental slope.

continental slope. The relatively steep slope from the outer edge of the continental shelf down to the more gently sloping ocean depths of the continental rise or abyssal plain.

convergent plate boundary. A boundary between two plates that are moving toward each other. Essentially synonymous with "subduction zone" but used in different contexts.

creep. The slow, imperceptible downslope movement of mineral, rock, and soil particles under gravity.

cross-bedding. Uniform to highly varied sets of inclined beds deposited by wind or water that indicate flow conditions such as direction and depth.

debris flow. A moving mass of rock fragments, soil, and mud, with more than half of the particles larger than sand size. Slow debris flows may move less that 1 m (3 ft) per year; rapid ones reach 160 kph (100 mph).

delta. The low, nearly flat, alluvial tract of land at or near the mouth of a river, commonly forming a triangular or fan-shaped plain of considerable area; resulting from the accumulation of sediment supplied by the river in such quantities that it is not removed by tides, waves, and currents.

diabase. An intrusive igneous rock consisting primarily of the minerals labradorite and pyroxene.

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

diorite. A coarse-grained, intrusive igneous rock characteristically containing plagioclase, as well as dark-colored amphibole (especially hornblende), pyroxene, and sometimes a small amount of quartz; diorite grades into monzodiorite with the addition of alkali feldspar.

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

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

displacement. The relative movement of the two sides of a fault; also, the specific amount of such movement.

divergent plate boundary. A boundary between two plates that are moving apart, characterized by mid-ocean ridges at which sea-floor spreading occurs.

ductile. Describes a rock that is able to sustain deformation such as folding, bending, or shearing before fracturing.

dune. A low mound or ridge of sediment, usually sand, deposited by the wind.

ebb-tidal delta. A tidal delta formed on the seaward side of a tidal inlet.

epicenter. The point on Earth's surface directly above the initial rupture point of an earthquake.

erosion. The general process or group of processes that loosen, dissolve, wear away, and simultaneously move from one place to another, the materials of Earth's crust; includes weathering, solution, abrasive actions, and transportation, but usually excludes slope movements.

escarpment. A steep cliff or topographic step resulting from vertical displacement on a fault or as a result of slope movement or erosion. Synonymous with "scarp."

estuary. The seaward end or tidal mouth of a river where freshwater and seawater mix.

eustatic. Describes a worldwide rise or fall in sea level.

extension. Deformation of Earth's crust whereby rocks are pulled apart.

extrusive. Describes an igneous rock that has been erupted onto the surface of the Earth. Extrusive rocks include lava flows and pyroclastic material such as volcanic ash.

fault. A break in rock characterized by displacement of one side relative to the other.

felsic. Derived from feldspar +silica to describe an igneous rock having abundant light-colored minerals such as quartz, feldspars, or muscovite; also, describes those minerals.

fissile. Capable of being easily split along closely spaced planes.

fissure. A fracture or crack in rock along which there is a distinct separation; commonly filled with mineral-bearing materials.

floodplain. The surface or strip of relatively smooth land composed of alluvium and adjacent to a river channel, constructed by the present river in its existing regimen and covered with water when the river overflows its banks. A river has one floodplain and may have one or more terraces representing abandoned floodplains.

fluvial. Of or pertaining to a river or rivers.

fold. A curve or bend in an originally flat structure, such as a rock stratum, bedding plane, or foliation; usually a product of deformation.

foraminifer. Any protozoan belonging to the subclass Sarcodina, order Foraminiferida, characterized by the presence of a test of one to many chambers composed of secreted calcite (rarely silica or aragonite) or of agglutinated particles; most foraminifers are marine but freshwater forms are known. Range: Cambrian to Holocene.

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

fossil. A remain, trace, or imprint of a plant or animal that has been preserved in the Earth's crust since some past geologic time; loosely, any evidence of past life.

fracture. The breaking of a mineral other than along planes of cleavage. Also, any break in a rock such as a crack, joint, or fault.

gabbro. A group of dark-colored, coarse-grained intrusive igneous rocks composed of plagioclase, pyroxene, amphibole, and olivine.

gastropod. Any mollusk belonging to the class Gastropoda, characterized by a distinct head with eyes and tentacles and, in most, by a single calcareous shell that is closed at the apex, sometimes spiraled, not chambered, and generally asymmetrical. Range: Upper Cambrian to Holocene.

geology. The study of Earth, including its origin, history, physical processes, components, and morphology.

geomorphology. The study of the general configuration of surface landforms and their relationships to underlying structures, and of the history of geologic changes as recorded by these surface features.

geothermal. Pertaining to the heat of the interior of the Earth.

granite. A coarse-grained, intrusive igneous rock in which quartz constitutes 10%–50% of the felsic ("light-colored") components and the alkali feldspar/total feldspar ratio is generally restricted to the range of 65% to 90%; perhaps the best known of all igneous rocks.

granodiorite. A coarse-grained intrusive igneous rock intermediate in composition between quartz diorite and quartz monzonite, containing quartz, plagioclase, and potassium feldspar as the felsic ("light-colored") components, with biotite, hornblende, or, more rarely, pyroxene, as the mafic ("dark-colored") components.

gravel. An unconsolidated, natural accumulation of typically rounded rock fragments resulting from erosion; consists predominantly of particles larger than sand; that is, greater than 2 mm (1/12 in) across.

graywacke. A dark gray, firmly indurated, coarse-grained sandstone that consists of poorly sorted angular to subangular grains of quartz and feldspar, with a variety of dark rock and mineral fragments embedded in a compact clayey matrix.

greenstone. A general term for any compact, dark-green, altered or metamorphosed basic igneous rock with a green color due to chlorite, actinolite, or epidote mineral content.

groundwater. That part of subsurface water that is in the zone of saturation, including underground streams.

grus. A silica-rich sand derived from the weathering of a parent rock, usually granite.

hot spot. A volcanic center, 100–200 km (60–120 mi) across, persistent for at least a few tens of millions of year, with a surface expression, commonly at the center of a plate, that indicates a rising plume of hot mantle material.

hot spring. A thermal spring whose temperature is above that of the human body.

hydrogeology. The science that deals with subsurface waters and related geologic aspects of surface waters, including the movement of groundwater; the mechanical, chemical, and thermal interaction of groundwater with the porous medium; and the transport of energy and chemical constituents by the flow of groundwater. Synonymous with "geohydrology."

hydrothermal. Of or pertaining to hot water, to the action of hot water, or to the products of this action.

hydrothermal water. Subsurface water whose temperature is high enough to make it geologically or hydrologically significant, whether or not it is hotter than the rock containing it.

igneous. Describes a rock or mineral that solidified from molten or partly molten material; also, describes processes leading to, related to, or resulting from the formation of such rocks. One of the three main classes or rocks—igneous, metamorphic, and sedimentary.

indurated. Describes a rock or soil hardened or consolidated by pressure, cementation, or heat.

inlet. A small, narrow opening, recess, indentation, or other entrance into a shoreline through which water penetrates into the land; or a waterway entering a sea, lake, or river. Also, a short, narrow waterway between islands, or connecting a bay, lagoon, or similar body of water with a larger body of water.

intertidal. Pertaining to the benthic ocean environment or depth zone between high water and low water; also, pertaining to the organisms of that environment. Synonymous with "littoral."

intrusion. The process of emplacement of magma into preexisting rock. Also, the igneous rock mass formed.

intrusive. Pertaining to intrusion, both the process and the rock body.

isotopic age. An age (in years) calculated from the quantitative determination of radioactive elements and their decay products.

isotopic dating. Calculating an age in years for geologic materials by measuring the presence of a short-lived radioactive element (e.g., carbon-14) or by measuring the presence of a long-lived radioactive element plus its decay product (e.g., potassium-40/argon-40). The term applies to all methods of age determination based on nuclear decay of naturally occurring radioactive isotopes.

jasper. A variety of chert containing iron-oxide impurities that give it various colors, characteristically red.

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

karst. A type of topography that is formed on limestone, gypsum, and other soluble rocks, primarily by dissolution. It is characterized by sinkholes, caves, and underground drainage.

lagoon. A narrow body of water that is parallel to the shore and between the mainland and a barrier island; characterized by minimal or no freshwater influx and limited tidal flux, which cause elevated salinities. Also, a shallow body of water enclosed or nearly enclosed within an atoll.

landslide. A collective term covering a wide variety of slope-movement landforms and processes that involve the downslope transport of soil and rock material en masse under the influence of gravity.

lava. Molten or solidified magma that has been extruded though a vent onto Earth's surface.

leaching. The separation, selective removal, or dissolving-out of soluble constituents from a rock or orebody by the natural action of percolating water.

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

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

levee. A long broad low embankment of sand and coarse silt built by floodwater overflow along both banks of a stream channel.

light detection and ranging/LiDAR. A method and instrument that measures distance to a reflecting object by emitting timed pulses of light and measuring the time between emission and reception of reflected pulses; the measured interval is converted to distance.

limestone. A carbonate sedimentary rock consisting of more than 95% calcite and less than 5% dolomite.

liquefaction. The transformation of loosely packed sediment into a more tightly packed fluid mass.

lithification. The conversion of sediment into solid rock.

lithify. To change to stone, especially to consolidate from a loose sediment to a solid rock.

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

longshore current. A current parallel to a coastline caused by waves approaching the shore at an oblique angle.

mafic. Derived from magnesium + ferric (Fe is the chemical symbol for iron) to describe an igneous rock having abundant dark-colored, magnesium- or iron-rich minerals such as biotite, pyroxene, or olivine; also, describes those minerals.

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

mantle. The zone of the Earth below the crust and above the core.

marine terrace. A relatively flat-topped, horizontal or gently inclined, surface of marine origin along a coast, commonly veneered by a marine deposit (typically silt, sand, or fine gravel).

mass wasting. Dislodgement and downslope transport of a mass of rock and/or unconsolidated material under the direct influence of gravity. In contrast to "erosion," the debris removed is not carried within, on, or under another medium. Synonymous with "slope movement."

matrix. The fine-grained material between coarse grains in an igneous or sedimentary rock. Also refers to rock or sediment in which a fossil is embedded.

mélange. A body of jumbled rock that is mappable at a scale of 1:24,000 or smaller and includes fragments and blocks of all sizes embedded in a fragmented and generally sheared matrix.

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

metamorphism. The mineralogical, chemical, and structural changes of solid rocks, generally imposed at depth below the surface zones of weathering and cementation.

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

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

mud flat. A relatively level area of fine silt along a shore or around an island, alternately covered and uncovered by the tide, or covered by shallow water; a muddy tidal flat, barren of vegetation.

mollusk. A solitary invertebrate such as gastropods, bivalves, and cephalopods belonging to the phylum Mollusca. Range: Lower Cambrian to Holocene.

normal fault. A fault in which the hanging wall appears to have moved downward relative to the footwall; the angle of dip is usually 45°–90°.

oceanic crust. Earth's crust that underlies the ocean basins and is rich in iron and magnesium; ranges in thickness from about 5 to 10 km (3 to 6 mi).

oceanic trench. A narrow, elongated depression, which may be thousands of kilometers long, of the deep-sea floor associated with a subduction zone, oriented parallel to a volcanic arc and usually to the edge of the adjacent continent; commonly 2 km (1 mi) or more deeper than the surrounding ocean floor.

ophiolite. An assemblage of ultramafic and mafic intrusive and extrusive igneous rock, probably representing oceanic crust.

orogeny. A mountain-building event.

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

paleogeography. The study, description, and reconstruction of the physical landscape in past geologic periods.

paleontology. The study of the life and chronology of Earth's geologic past based on the fossil record.

passive margin. A continental plate boundary where no plate-scale tectonism is taking place; plates are not converging, diverging, or sliding past one another.

peridotite. A coarse-grained intrusive igneous rock composed primarily of olivine and other mafic minerals; commonly alters to serpentinite.

phenocryst. A relatively large, conspicuous crystal in a porphyritic rock.

plate boundary. A zone of seismic and tectonic activity along the edges of lithospheric plates, resulting from the relative motion among plates.

plate tectonics. A theory of global tectonics in which the lithosphere is divided into about 20 rigid plates that interact with one another at their boundaries, causing seismic and tectonic activity along these boundaries.

platform. Any level or nearly level surface.

plume. A persistent, pipelike body of hot material moving upward from Earth's mantle into the crust.

pluton. A deep-seated igneous intrusion.

plutonic. Describes an igneous rock or intrusive body formed at great depth beneath Earth's surface.

porosity. The percentage of total void space in a volume of rock or unconsolidated deposit.

porphyritic. An igneous rock texture in which larger crystals (phenocrysts) are set in a finer-grained matrix.

quartz. Silicon dioxide, SiO_2. The only silicate (silicon + oxygen) mineral consisting entirely of silicon and oxygen. Synonymous with "crystalline silica."

radiolarian. Any actinopod (protozoan) belonging to the subclass Radiolaria, characterized by a siliceous skeleton and a marine pelagic environment. Range: Cambrian to Holocene.

radiometric age. An age (in years) calculated from the quantitative determination of radioactive elements and their decay products. The preferred term is "isotopic age."

regolith. From the Greek "rhegos" (blanket) + "lithos" (stone), the layer of unconsolidated rock material that forms the surface of the land and overlies or covers bedrock; includes rock debris of all kinds, volcanic ash, glacial drift, alluvium, loess, and aeolian deposits, vegetal accumulations, and soil.

reverse fault. A contractional high-angle (greater than 45°) dip-slip fault in which the hanging wall moves up relative to the footwall.

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

right-lateral fault. A strike-slip fault on which the side opposite the observer has been displaced to the right.

riprap. A layer of large, durable rock fragments placed in an attempt to prevent erosion by water and thus preserve the shape of a surface, slope, or underlying structure.

rock. An aggregate of one or more minerals (e.g., granite), a body of undifferentiated mineral matter (e.g., obsidian), or a body of solid organic material (e.g., coal).

rockfall. The most rapid type of slope movement in which a newly detached fragment of bedrock of any size falls from a cliff or other very steep slope, traveling straight down or in a series of leaps and bounds down a slope.

sand. A clastic particle smaller than a granule and larger than a silt grain, with a diameter ranging from 1/16 to 2 mm (0.0025 to 0.08 in).

sandstone. Clastic sedimentary rock composed of predominantly sand-sized grains.

schist. A medium- to coarse-grained, strongly foliated, metamorphic rock with eminently visible mineral grains, particularly mica, which are arranged parallel, imparting a distinctive sheen, or "schistosity," to the rock.

seafloor spreading. A process whereby new oceanic crust is formed by upwelling of magma at the center of mid-ocean ridges and by a moving-away of the new material from the site of upwelling at rates of 1 to 10 cm (2 to 25 in) per year. This movement provides the source of seafloor within the theory of plate tectonics, which also contains a provision for destruction of seafloor by subduction.

seamount. An elevated portion of the sea floor, 1,000 m (3,300 ft) or higher, either flat-topped or peaked.

sediment. An eroded and deposited, unconsolidated accumulation of rock and mineral fragments.

sedimentary. Pertaining to or containing sediment.

sedimentary rock. A rock resulting from the consolidation of loose sediment that has accumulated in layers; it may be "clastic," consisting of mechanically formed fragments of older rock; "chemical," formed by precipitation from solution; or "organic," consisting of the remains of plants and animals. One of the three main classes of rock—igneous, metamorphic, and sedimentary.

sedimentation. The process of forming or accumulating sediment into layers, including the separation of rock particles from parent rock, the transportation of these particles to the site of deposition, the actual deposition or settling of the particles, the chemical and other changes occurring in the sediment, and the ultimate consolidation of the sediment into solid rock.

seismic. Pertaining to an earthquake or Earth vibration, including those that are artificially induced.

seismicity. The phenomenon of movements in the Earth's crust. Synonymous with "seismic activity."

sequence. A succession of geologic events, processes, or rocks, arranged in chronologic order to show their relative position and age with respect to geologic history as a whole. Also, a rock-stratigraphic unit that is traceable over large areas and defined by sediment associated with a major sea level transgression–regression.

serpentine. A group of silicate (silicon + oxygen) minerals with the general formula $(Mg,Al,Fe,Mn,Ni,Zn)_{2-3}(Si,Al,Fe)_2O_5(OH)_4$, characterized by a greasy or silky luster, a slightly soapy feel, and conchoidal fracture.

serpentinite. A nonfoliated, metamorphic rock characterized by mottled shades of green and a resemblance to the skin of a serpent; consists almost entirely of serpentine minerals.

shale. A clastic sedimentary rock made of clay-sized particles and characterized by fissility.

shear. Deformation resulting from stresses that cause contiguous parts of a body to slide relatively to each other in a direction parallel to their plane of contact.

shear zone. A zone of rock that has been crushed and brecciated by many parallel fractures as a result of shearing.

sheeted dikes. A swarm of parallel to subparallel igneous dikes so closely spaced that little or no intervening wall rock is preserved.

shoal. A relatively shallow place in a stream, lake, sea, or other body of water.

silica. Silicon dioxide, SiO_2, an essential constituent of many minerals, occurring as crystalline quartz, cryptocrystalline chalcedony, and amorphous opal.

silicate. A mineral group composed of silicon (Si) and oxygen (O) plus an element or elements, for example, quartz, SiO_2; olivine, $(Mg, Fe)_2SiO_4$; and pyroxene, $(Mg,Fe)SiO_3$; as well as the amphiboles, micas, and feldspars.

siliceous. Describes a rock or other substance containing abundant silica.

silt. Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay, 0.0039 to 0.063 mm (0.00015 to 0.0025 in) across.

slope. The inclined surface of any part of Earth's surface, such as a hillslope. Also, a broad part of a continent descending into an ocean.

slope movement. The gradual or rapid downslope movement of soil or rock under gravitational stress. Synonymous with "mass wasting."

slump. A generally large, coherent slope movement with a concave failure surface and subsequent backward rotation relative to the slope.

soil. The unconsolidated portion of the Earth's crust modified through physical, chemical, and biotic processes into a medium capable of supporting plant growth.

sorted. Describes an unconsolidated sediment consisting of particles of essentially uniform size.

speleothem. Any secondary mineral deposit that forms in a cave.

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

spring. A place where groundwater flows naturally from a rock or the soil onto the land surface or into a body of surface water.

storm surge. An abnormal, sudden rise of sea level along an open coast during a storm, caused primarily by strong winds offshore, or less frequently, a drop in atmospheric pressure, resulting in water piled up against the coast. It is most severe during high tide.

strata. Tabular or sheetlike layers of sedimentary rock that are visually distinctive from other layers above and below. The singular form of the term is stratum, but is less commonly used.

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

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

strike-slip fault. A fault with measurable offset where the relative movement is parallel to the strike of the fault. Described as left-lateral (sinistral) when relative motion of the block opposite the observer is to the left, and right-lateral (dextral) when relative motion is to the right.

subduction. The process of one lithospheric plate descending beneath another.

subduction zone. A long, narrow belt in which subduction takes place.

subsidence. The sudden sinking or gradual downward settling of part of Earth's surface.

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

syncline. A generally concave upward fold of which the core contains the stratigraphically younger rocks.

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

tectonic. Describes a feature or process related to large-scale movement and deformation of Earth's crust.

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

terrace. Any long, narrow, relatively level or gently inclined surface (i.e., a bench or steplike ledge) that is bounded along one edge by a steeper descending slope and along the other edge by a steeper ascending slope, thus breaking the continuity of the slope; commonly occurs along the margin and above the level of a body of water, marking a former water level.

terrane. A fault-bounded body of rock of regional extent, characterized by a geologic history different from that of contiguous terranes or bounding continents.

terrestrial. Describes a feature, process, or organism related to land, Earth, or its inhabitants.

test. The shell or internal skeleton of many invertebrates.

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

thermal. Pertaining to or caused by heat.

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

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

trace (structural geology). The intersection of a geological surface with another surface, for example, the trace of bedding on a fault surface, or the trace of a fault or outcrop on the ground.

trace fossil. A fossilized feature such as a track, trail, burrow, or coprolite (dung), that preserves evidence of an organism's life activities, rather than the organism itself. Compare to "body fossil."

transform fault. A strike-slip fault that links two other faults or plate boundaries such as two segments of a mid-ocean ridge.

transform plate boundary. A type of plate boundary at which lithosphere is neither created nor destroyed, and plates slide past each other on a strike-slip fault.

transpression. A combination of crustal shortening and strike-slip movement.

turbidite. Sediment or rock deposited from a turbidity current (underwater flow of sediment) and characterized by graded bedding, moderate sorting, and well-developed primary structures in the sequence noted by the Bouma cycle.

turbidity current. A bottom-flowing current laden with suspended sediment, moving swiftly (under the influence of gravity) down a subaqueous slope and spreading horizontally on the floor of the body of water.

ultramafic. Describes an intrusive igneous rock primarily composed of mafic minerals.

unconformity. A substantial break or gap in the geologic record where a rock unit is overlain by another that is not next in stratigraphic succession, resulting from either a change that caused deposition to cease for a considerable span of time or erosion with loss of the previously formed record.

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

uplift. A structurally high area in Earth's crust produced by movement that raises the rocks.

uranium-lead age method. ("U-Pb") Calculation of an age in years for geologic material based on the known radioactive decay rate of uranium-238 to lead-206 and uranium-235 to lead-207.

volcanic. Pertaining to the activities, structures, or rock types of a volcano. A synonym of extrusive.

weathering. The physical, chemical, and biological processes by which rock is broken down, particularly at Earth's surface.

Wisconsinan. Pertaining to the classical fourth glacial stage of the Pleistocene Epoch in North America, following the Sangamonian interglacial stage and preceding the Holocene Epoch.

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Additional References

This chapter lists additional references, resources, and websites that may be of use to resource managers. Web addresses are valid as of May 2016. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.

Geology of National Park Service Areas

- Golden Gate National Recreation Area: Geologic Activity: http://www.nps.gov/goga/learn/nature/geologicactivity.htm
- NPS Geologic Resources Division (Lakewood, Colorado) *Energy and Minerals; Active Processes and Hazards; Geologic Heritage*: http://go.nps.gov/geology
- NPS Geologic Resources Division Education Website: http://go.nps.gov/geoeducation
- NPS Geologic Resources Inventory: http://go.nps.gov/gri
- NPS Geoscientists-in-the-Parks (GIP) internship and guest scientist program: http://go.nps.gov/gip
- NPS Views program (geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a variety of geologic parks): http://go.nps.gov/views
- USGS Geology of National Parks (including 3D imagery): http://3dparks.wr.usgs.gov/

NPS Resource Management Guidance and Documents

- Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html
- 1998 National parks omnibus management act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf
- NPS-75: Natural resource inventory and monitoring guideline: http://www.nature.nps.gov/nps75/nps75.pdf
- NPS Natural resource management reference manual #77: http://www.nature.nps.gov/Rm77/
- Geologic monitoring manual (Young and Norby 2009): http://go.nps.gov/geomonitoring
- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://www.nps.gov/dsc/technicalinfocenter.htm

Climate Change Resources

- NPS Climate Change Response Program Resources: http://www.nps.gov/subjects/climatechange/resources.htm
- US Global Change Research Program: http://globalchange.gov/home
- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/

Geological Surveys and Other Organizations

- California Geological Survey: http://www.consrv.ca.gov/CGS/Pages/Index.aspx
- State of California Multi-Hazard Mitigation Plan 2013: http://www.caloes.ca.gov/cal-oes-divisions/hazard-mitigation/hazard-mitigation-planning/state-hazard-mitigation-plan
- 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/
- Southern California Earthquake Center: https://www.scec.org/
- California Earthquake Authority: http://www2.earthquakeauthority.com/
- The Bay Area Earthquake Alliance: http://bayquakealliance.org/
- University of California Berkeley Seismological Laboratory: http://seismo.berkeley.edu/

US Geological Survey Reference Tools

- National geologic map database (NGMDB): http://ngmdb.usgs.gov/
- Geologic names lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html

- Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/
- GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")
- Publications warehouse (many publications available online): http://pubs.er.usgs.gov
- Tapestry of time and terrain (descriptions of physiographic provinces): http://pubs.usgs.gov/imap/i2720/

San Francisco Bay Area Geology Guidebooks

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Appendix A: Scoping Participants

The following people attended the GRI scoping meeting for Golden Gate National Recreation Area, including Fort Point National Historic Site and Muir Woods National Monument, held on 26-28 September 2007, or the follow-up report writing conference call, held on 6 May 2014. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website, http://go.nps.gov/gripubs.

2007 Scoping Meeting Participants

Name	Affiliation	Position
Sarah Allen	Point Reyes National Seashore	Science Advisor
Patrick Barnard	US Geological Survey	Coastal Geologist
Mark Borrelli	NPS Geologic Resources Division	Geologist
Guy Cochrane	US Geological Survey	Geophysicist
Tim Connors	NPS Geologic Resources Division	Geologist
Gary Davis	NPS (retired)	Science Advisor
Marsha Davis	Pacific West Regional Office	Regional Geologist
Marie Denn	Point Reyes National Seashore	Ecologist
Will Elder	Golden Gate National Recreation Area	Interpreter
Russ Graymer	US Geological Survey	Geologist
Daphne Hatch	Golden Gate National Recreation Area	Chief of Natural Resources
Bruce Heise	NPS Geologic Resources Division	Geologist/GRE Program Coordinator
Sam Johnson	US Geological Survey	Coastal Geologist
Katie KellerLynn	Colorado State University	Geologist/Research Associate
Brannon Ketcham	Point Reyes National Seashore	Hydrologist
Marcus Koenen	San Francisco Bay Area Network	Network Coordinator
Greg Mack	Pacific West Region	Geologist
Bonnie Murchey	US Geological Survey	Geologist
Tania Pollak	Presidio Trust	Natural Resource Planner
Dale Roberts	PORE-Cordell Bank-NOAA	Biologist
Judy Rocchio	Pacific West Region	Physical Scientist
Craig Scott	Golden Gate National Recreation Area	GIS Specialist
William Shook	Point Reyes National Seashore	Chief of Natural Resources
Phil Stoffer	U.S. Geological Survey	Geologist
Terri Thomas	Presidio Trust	Natural Resource Chief
Ed Ueber	National Marine Sanctuary	Ocean Superintendent
Kristen Ward	Golden Gate National Recreation Area	Ecologist
Tamara Williams	Golden Gate National Recreation Area	Hydrologist
Chris Wills	California Geological Survey	Geologist

2014 Conference Call Participants

Name	Affiliation	Position
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Laura Castellini	Golden Gate National Recreation Area	Engineering Technician
Tim Connors	NPS Geologic Resources Division	Geologist
Will Elder	Golden Gate National Recreation Area	Interpreter
Darren Fong	Golden Gate National Recreation Area	Aquatic Ecologist
Peter Gavette	Golden Gate National Recreation Area	Archaeologist
Daniel George	NPS San Francisco Bay Area Network	Network I&M Program Manager
Daphne Hatch	Golden Gate National Recreation Area	Chief of Natural Resources
Samuel Johnson	US Geological Survey	Coastal Geologist
Jason Kenworthy	NPS Geologic Resources Division	Geologist, GRI reports coordinator
Rebecca Port	NPS Geologic Resources Division	Geologist, Technical Writer and Editor
Vincent Santucci	NPS Geologic Resources Division	Geologist, Washington Liaison
Brian Ullensvang	Golden Gate National Recreation Area	Environmental Engineer
Kristen Ward	Golden Gate National Recreation Area	Ecologist
Chris Wills	California Geological Survey	Geologist

Appendix B: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to National Park Service 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. Information is current as of June 2016. Contact the NPS Geologic Resources Division for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Paleontology	**National Parks Omnibus Management Act of 1998, 16 USC § 5937** 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. Regulations in association with 2009 PRPA are being finalized (August 2015).	**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.
Rocks and Minerals	**NPS Organic Act, 16 USC § 1 et seq.** directs the NPS to conserve all resources in parks (including rock and mineral resources), unless otherwise authorized by law.	**36 CFR § 2.1** prohibits possessing, destroying, disturbing mineral resources… in park units. **Exception: 36 CFR § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, or 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.
Park Use of Sand and Gravel	**Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units.	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.

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.
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, 16 USC § 5937** protects the confidentiality of the nature and specific location of cave and karst resources.	**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.

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).
Coastal Features and Processes	**NPS Organic Act, 16 USC § 1 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.

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 13653** (Preparing the United States for the Impacts of Climate Change) (2013) outlines Federal agency responsibilities in the areas of supporting climate resilient investment; managing lands and waters for climate preparedness and resilience; providing information, data and tools for climate change preparedness and resilience; and planning. **Executive Order 13693** (Planning for Federal Sustainability in the Next Decade) (2015) established to maintain Federal leadership in sustainability and greenhouse gas emission reductions. **President's Climate Action Plan** (2013), http://www.whitehouse.gov/sites/default/files/image/president27sclimateactionplan.pdf	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). **NPS Climate Change Response Strategy** (2010) describes goals and objectives to guide NPS actions under four integrated components: science, adaptation, mitigation, and communication. **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. **DOI Manual Part 523, Chapter 1** establishes policy and provides guidance for addressing climate change impacts upon the Department's mission, programs, operations, and personnel. **Revisiting Leopold: Resource Stewardship in the National Parks** (2012) will guide US National Park natural and cultural resource management into a second century of continuous change, including climate change. **Climate Change Action Plan** (2012) articulates a set of high-priority no-regrets actions the NPS will undertake over the next few years **Green Parks Plan** (2013) is a long-term strategic plan for sustainable management of NPS operations.

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

NPS 641/133748, 400/133748, 112/133748, August 2016

National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science
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Geologic Map of Golden Gate NRA, Fort Point NHS, and Muir Woods NM

California

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science

Sheet 1: San Francisco and San Mateo Counties

Geologic Map of Golden Gate NRA, Fort Point NHS, and Muir Woods NM

California

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science

Sheet 2: Marin County

This map displays geologic map data compiled by the National Park Service Geologic Resources Inventory. It is not a substitute for site-specific investigations.

Source Map
The source maps used in creation of the digital geologic data product include a California Geological Survey publication and US Geological Survey publications (see "Geologic Map Data" section in the GRI report for specific sources).

Source Scales 1:24,000 and 1:100,000
According to US National Map accuracy standards, features are expected to be within 12 m (40 ft) or 50 m (166 ft) of their true location.

Poster Layout
Chase Winters and Georgia Hybels (Colorado State University)
Poster Date
August 2016
GRI Data Date
January 2016
Source Map Dates
Published between 1958 and 2006

All Geologic Resources Inventory geologic map data and publications are available at http://go.nps.gov/gripubs.

Map Unit Properties Table: Golden Gate National Recreation Area, including Fort Point National Historic Site and Muir Woods National Monument

This table only contains geologic map units that are mapped within the park's authorized boundary. If a map unit occurs within the NPS-managed area of the authorized boundary, the table lists where each unit is mapped. For clarity, some map units are grouped by rock or deposit type and therefore may not be listed in chronostratigraphic order. Bold text corresponds to sections in the report. Refer to the goga_geology.pdf in the GRI GIS data for detailed descriptions of all geologic map units, including those not mapped within the authorized boundary of the park.

Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY	Undifferentiated surficial deposits (**Qu**)	**Qu** includes artificial fill, beach sand, marine deposits, alluvium, landslides, and some Colma Formation (**Qc**). **Qu** is mapped within the managed area of the park at Fort Point, Dias Ridge, and in the Marin Headlands.	**Cenozoic Rocks and Deposits**—**Qu** includes manufactured debris in artificial fill; see artificial fill units for more information. **Landslide Deposits and Slope Movements—Qu** includes landslide deposits; see landslide deposits for more information. **Alluvium and Fluvial Processes—Qu** includes alluvium; see alluvium units for more information. **Coastal Features and Processes—Qu** includes beach sand and marine deposits; see beach and dune deposits for more information. See also Colma Formation (**Qc**) for more information.	**Earthquake, Probability, Hazards, and Risks—**artificial fill and unconsolidated material, especially if wet and/or placed over former bay floors, is likely to shake intensely during earthquakes and is highly susceptible to liquefaction. See also Colma Formation (**Qc**) for more information.	**Evolution of the Modern Landscape—**as a group, these include the youngest deposits in the park. Surficial deposits were created by a variety of processes over the past two million years, and in the case of artificial fill, within the past century or so of human modification. See also Colma Formation (**Qc**) for more information.
QUATERNARY	**ARTIFICIAL FILL UNITS** Artificial fill (**Qar**) Artificial fill over marine and marsh deposits (**Qmf**) Artificial fill, development related (**Qf1**)	Gravel, sand, silt, clay, rock fragments, organic material, and manufactured debris. Unconsolidated to very well consolidated. **Qmf** is fill placed on top of tidal flats and marshes which are composed of silty-clay similar to **Qbmo**. **Qf1** is fill made before 1965 and was almost always not compacted. Fill consists simply of dumped materials. Artificial fill is mapped within the managed area of the park in the Marin Headlands, on Alcatraz, and many locations on the San Francisco Peninsula (Mori Point, Corral de Tierra, Sweeney Ridge, Sneath Lane, Mussel Rock, Fort Miley East, Ocean Beach/Fort Funston, Fort Mason, Fort Point, and Crissy Field).	**Cenozoic Rocks and Deposits**—development over much of the San Francisco Peninsula required the use of artificial fill. Marsh restoration activities at Crissy Field removed artificial fill. **Qf1** includes spoil from tunneling operations. **Qf1** is used in riprap and the construction of highways, railroads, and airport runways, as well as earthfill dams, reservoir embankments, building-site grades, and sanitary landfills. **Coastal Features and Processes—Qar** includes some dune sand.	**Earthquake, Probability, Hazards, and Risks—**artificial fill, especially if unconsolidated and/or placed into the bay, is likely to shake intensely during earthquakes and is highly susceptible to liquefaction. **Disturbed Land Restoration—**many disturbed lands throughout the park, including Crissy Field and others underlain by artificial fill, have been targeted for restoration.	**Evolution of the Modern Landscape—**humans have long modified, and continue to modify, the landscape of the Bay Area, including efforts to restore disturbed landscapes.
QUATERNARY	**ESTUARINE DEPOSITS AND MUD** Basin deposits (**Qhb**) Bay mud, younger (**Qbmy**) Bay mud, older (**Qbmo**)	Silt, clay, organic matter, and some fine sand. Generally unconsolidated, but older deposits may be moderately consolidated. Commonly interfingers with fine-grained alluvium. Thickness may be as much as 30 m (100 ft). These deposits are not mapped within the managed area of the park. Within the authorized boundary, **Qhb** is mapped along the south end of Upper Crystal Springs Reservoir, and **Qbmy** and **Qbmo** are mapped around Tomales Bay.	**Coastal Features and Processes**—these units were all deposited at or near sea level. **Qhb** was deposited on a flat-floored basin at the distal edge of an alluvial fan. **Qbmy** and **Qbmo** were deposited in estuaries around Tomales Bay.	**Earthquake, Probability, Hazards, and Risks—**unconsolidated units, especially those saturated with water, are likely to shake intensely due to earthquakes and are susceptible to liquefaction. When wet, **Qbmo** deposits have a moderate to high potential for liquefaction. **Qbmo** deposits are soft and plastic when wet (common near the top) and firm when dry (usually occurring at depth). **Sea Level Rise—**sea level is predicted to rise by roughly 1 m (3 ft) by the end of this century; the area covered by these units would undoubtedly be affected.	**Evolution of the Modern Landscape—**cores taken from San Francisco Bay recorded as many as seven interglacial periods (indicated by estuarine rocks which correspond to times of high sea level) over the last 500,000 years

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY	**BEACH AND DUNE DEPOSITS** Beach sand (**Qbs**) Dune sand – younger (**Qdsy**) Older beach deposits (**Qob**)	Predominantly loose, well sorted beach and dune sand. Includes some pebble and cobble beaches. Thickness generally less than 6 m (20 ft) but may exceed 30 m (98 ft). Beach and dune deposits are mapped in many managed areas within the park, notably at Stinson Beach, Muir Beach, Tennessee Beach, Rodeo Beach, Crissy Field, Baker Beach, and Ocean Beach.	**Coastal Features and Processes—**these units comprise the sandy beaches and dunes in the park. Primary sediment sources are offshore submerged ancient sand dunes and weathering of local rocks. Beaches tend to be wider in summer and narrower in winter. Many of the beaches in the park have been either eroding or accreting for long periods. Dunes are mapped over the majority of the north end of the San Francisco Peninsula, however much of this area is now covered by development.	**Earthquake, Probability, Hazards, and Risks—**unconsolidated units, especially those saturated with water, are likely to shake intensely due to earthquakes and are susceptible to liquefaction. **Sea Level Rise—**sea level is predicted to rise by roughly 1 m (3 ft) by the end of this century; the area covered by these units would undoubtedly be affected. **Coastal Erosion and Sediment Dynamics—**these units and associated infrastructure have been impacted by coastal erosion. A notable example is the southern section of Ocean Beach, where erosion has been occurring for decades. Where human activities are responsible for increased erosion and altered sediment dynamics, intervention is permitted according to NPS policy. **Monitoring Aeolian Resources—**dunes protect the shoreline and provide important habitat. Monitoring dune fields could assist in determining trends and identifying which areas require protection	**Evolution of the Modern Landscape—**beaches and dunes on the modern landscape continue to evolve. Some beaches and dunes date back to the Pleistocene Epoch.
QUATERNARY	**ALLUVIUM** Younger alluvium (**Qya**) Holocene alluvial fan deposits (**Qafy**) Alluvium, undivided, younger (**Qaly**) Alluvium, undivided, older (**Qalo**) Older alluvium (**Qoal**) Pleistocene alluvial terrace deposits (**Qpaf1**)	Unconsolidated, poorly sorted gravel, sand, silt, and clay in various proportions and combinations. Organic matter such as wood fragments is common. Stream terrace alluvium (**Qpaf1**) is coarsest grained with clasts up to 35 cm (14 in) in diameter. Graded bedding is common; gravel and sand tend to fine upward to sandy or silty clay. Deposits are coarser in the headward reaches of stream valleys. Some cross-bedding occurs. In many places **Qya** is included with other alluvial deposits because of map scale limitations. Older alluvium (**Qoal**) may be moderately consolidated. Within the managed area of the park, alluvium is mapped south of the Golden Gate in the valleys of Corral de Tierra (e.g., along San Vicente Creek and Denniston Creek), in Calera Valley southeast of Sweeney Ridge, and in the Phleger Estate. North of the Golden Gate it is mapped where gulches enter into Bolinas Lagoon at Stinson Beach and in all the major valleys of the Marin Headlands (e.g., Tennessee Valley, Green Gulch, Frank Valley, Gerbode Valley, along Bunker Road). Older alluvium (**Qoal**) is mapped in Olema Valley.	**Paleontological Resources—Qaly** and **Qalo** deposits contain fossils of extant vertebrate and invertebrates. **Alluvium and Fluvial Processes**—flowing water deposited alluvium in drainage channels such as streams and valleys, on alluvial fans, as stream terraces and levees, on floodplains, and in basins.	**Earthquake, Probability, Hazards, and Risks—**unconsolidated units, especially those saturated with water, are likely to shake intensely due to earthquakes and are susceptible to liquefaction, though they are less susceptible than **Qmf** and **Qu**. **Groundwater Contamination—**pollutants tend to follow high-porosity stream channel and levee deposits. **Flooding—**flood potential on alluvial fans is a concern because models do not account for the shifting nature of alluvial fans. **Paleontological Resource Inventory, Monitoring, and Protection—**threats to paleontological resources in the park include unauthorized collecting, vandalism, and erosion.	**Evolution of the Modern Landscape—**deposited in a variety of flowing water environments during the Pleistocene and Holocene (the past 2.6 million years).

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY	**LANDSLIDE DEPOSITS** Younger landslide deposits (**Qyl**) Landslide deposits (**Qls**) Slope and ravine debris (**Qsr**) Colluvium (**Qcl**) Older landslide deposits (**Qol**)	Generally, unconsolidated to moderately consolidated, unsorted to poorly sorted rock fragments of all sizes, sand, silt, clay, and some organic material. Composition and structure of each deposit depends on the geologic formation involved and type of landslide. May include small alluvial deposits. Due to map scale limitations, more landslide deposits may be present than are shown on the map. Throughout Corral de Tierra, "small mass movements" are abundant on slopes (see "Hazard Point Features" in GRI GIS data), and slope and ravine debris consisting of weathered granitic rock (**Kgr**) fills valleys. The valleys around Mori Point, Sweeney Ridge, and Milagra Ridge contain landslide deposits of weathered Franciscan rocks ("**Kf**" and "**KJf**" map units). The coast along Mussel Rock contains landslide deposits emanating from the Merced Formation (**QTm**). Landslide deposits of weathered mélange occur along the coast at Land's End and of weathered serpentinite north of Baker Beach. In the Marin Headlands, landslide deposits are conspicuous along US 101; they are less so in the interior. Landslide deposits of weathered mélange are present along Muir Beach.	**Landslide Deposits and Slope Movements**—landslide deposits resulted from slow to rapid downslope transport of soil and rock under the influence of gravity. Landslide deposits in the park include creep deposits, debris flows, and block slumps. Maximum accumulations of landslide deposits occur near bases of slopes underlain by sheared rock of the Franciscan Complex ("**Kf**" and "**KJf**" map units) and granitic rocks of Montara Mountain (**Kgd**). Along Mussel Rock, landslides appeared to have emanated from the Merced Formation (**QTm**). **Alluvium and Fluvial Processes**—unconcentrated surface runoff (e.g., rainwash, sheetwash) in combination with slope movements deposited slope and ravine debris (**Qsr**) and colluvium (**Qcl**).	**Earthquake, Probability, Hazards, and Risks—** unconsolidated units, especially those saturated with water, are likely to shake intensely due to earthquakes and are susceptible to liquefaction. **Slope Movement Hazards and Risks—**current landslide distribution is a good first order indicator of future landslide activity. Small, shallow landslides are abundant within slope and ravine debris (**Qsr**). Younger landslide deposits (**Qyl)** are considered active and unstable. Older deposits (**Qol**) are assumed to be inactive and/or stabilized, as no evidence of recent movement has been observed. However, they are susceptible to reactivation by unusually high or prolonged rainfall, earthquakes, and/or improper grading or drainage procedures.	**Evolution of the Modern Landscape—**deposited by slope movements that occurred during the Holocene and potentially the Pleistocene.
QUATERNARY	Marine terrace deposits (**Qtmr**)	Unconsolidated to moderately consolidated sand, silt, gravel, and clay on marine terraces (uplifted wave-cut platforms). Variable thickness, but probably everywhere less than 30 m (98 ft). Within the managed area of the park, marine terrace deposits occur near the coast in Corral de Tierra and Mori Point, and on the coastal bluffs south of Mussel Rock.	**Alluvium and Fluvial Processes—**the upper portion of a marine terrace deposit is commonly formed by sub-aerial deposition and includes alluvial gravel, colluvial clay, and stream terrace deposits which form rounded and subdued topography. **Coastal Features and Processes—**the lower portion of a marine terrace deposit is commonly of marine origin and includes beach deposits and younger aeolian (dune) sands which form near-vertical cliffs along the coast.	**Earthquake, Probability, Hazards, and Risks—** unconsolidated units, especially those saturated with water, are likely to shake intensely due to earthquakes and are susceptible to liquefaction.	**Evolution of the Modern Landscape—**marine terraces (upon which **Qtmr** sits) originated as wave-cut platforms which formed at sea level when relative sea level was higher than it is today. As sea level dropped and/or uplift occurred, these platforms became exposed. Today, they are evidence of the location of ancient coastlines.
QUATERNARY	Colma Formation (**Qc**)	Weakly consolidated, fine to medium grained sand with minor sandy silt, clay, and gravel interbeds. Thin to thick bedded, rarely massive. Beds are evenly spaced and either nearly horizontal or cross-bedded. Zones of scattered well-rounded and polished chert pebbles. Thickness unknown, but probably exceeds 30 m (100 ft). The Colma Formation is only mapped east of the San Andreas Fault. Within the managed area of the park, it is mapped in a few locations along Baker Beach, Land's End, and Ocean Beach where the formation is developed up to 150 m (500 ft) above sea level as coastal bluffs. **Qu** includes some Colma Formation.	**Cenozoic Rocks and Deposits—Qc** was deposited in a shallow marine environment during the Cenozoic Era. The sands of the Colma Formation form a good aquifer and springs are common at the contact with the underlying serpentinite at the Presidio. **Paleontological Resources—Qc** has produced mammoth fossils from within Golden Gate National Recreation Area. **Coastal Features and Processes—Qc** represents both shallow bay deposition and valley-slope debris and may include sediments that were originally deposited as dune sand. Today, the Colma Formation forms coastal bluffs.	**Paleontological Resource Inventory, Monitoring, and Protection—**threats to paleontological resources in the park include unauthorized collecting, vandalism, and erosion.	**Evolution of the Modern Landscape—**the Colma Formation is a shallow marine deposit. The sand accumulated from 125,000 to 80,000 years ago (Pleistocene Epoch) during an interglacial period when sea level was slightly higher than today (Elder 2001).

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY (late Pleistocene)	Olema Creek Formation (**Qoc**)	Granitic sand and gravel interbedded with mud and peat. South of Tomales Bay, thickness is as much as 170 m (558 ft). The Olema Creek Formation is mapped south of the town of Olema amidst the San Andreas Fault system. It is not mapped in the managed areas of the park.	**Cenozoic Rocks and Deposits—**the Olema Creek Formation is of alluvial and estuarine origin; sediments accumulated on a coastal plain at the head of Tomales Bay at about the same time as the deposition of the Millerton Formation (**Qml**) (Pleistocene Epoch).	None documented.	**Evolution of the Modern Landscape—**deposited in streams and estuaries at head of Tomales Bay. It is approximately contemporaneous with the Millerton Formation (**Qml**).
QUATERNARY (late Pleistocene)	Millerton Formation (**Qml**)	Clay, silt, sand, and gravel. Along the eastern margin of Tomales Bay, thickness is as much as 30 m (98 ft). The Millerton Formation is mapped along the eastern margin of Tomales Bay, amidst the San Andreas Fault system. It is not mapped in the managed areas of the park.	**Cenozoic Rocks and Deposits—**the Millerton Formation is of alluvial and estuarine origin; sediments accumulated on terraces along the eastern margin of Tomales Bay at about the same time as the deposition of the Olema Creek Formation (**Qoc**) (Pleistocene Epoch). **Paleontological Resources—Qml** contains abundant fossil fauna and flora.	**Paleontological Resource Inventory, Monitoring, and Protection—**threats to paleontological resources in the park include unauthorized collecting, vandalism, and erosion.	**Evolution of the Modern Landscape—**deposited in streams and estuaries along eastern margin of Tomales Bay. It is approximately contemporaneous with the Olema Creek Formation (**Qoc**).
QUATERNARY AND NEOGENE (lower Pleistocene and upper Pliocene)	Santa Clara Formation (**QTsc**)	Moderately consolidated, poorly sorted and indurated conglomerate and pebbly to cobbly sand, silt, and clay in irregular and lenticular beds. Pebbles and cobbles are angular to sub-rounded. Contains a tuff bed near Woodside. Reaches a maximum thickness of about 500 m (1640 ft) along Coal Mine Ridge (southeast of the Phleger Estate and at the south end of Portola Valley). **QTsc** is mapped south of San Francisco, amidst the San Andreas Fault system. In the managed area of the park, the Santa Clara Formation is mapped in the Phleger Estate and in one small location at Sweeney Ridge.	**Cenozoic Rocks and Deposits—**late Pliocene uplift and erosion of Franciscan graywacke and greenstone resulted in deposition of the terrestrial sediments of the Santa Clara Formation probably as an alluvial fan. **QTsc** is the contemporaneous terrestrial equivalent of the marine Merced Formation (QTm). **Paleontological Resources—**gray to buff claystone and siltstone beds of **QTsc** on Coal Mine Ridge contain carbonized wood fragments as large as 60 cm (24 in) in diameter.	**Paleontological Resource Inventory, Monitoring, and Protection—**threats to paleontological resources in the park include unauthorized collecting, vandalism, and erosion.	**Evolution of the Modern Landscape—**represent northwest–flowing braided stream deposits and probably indicate the development of the modern San Francisco watershed during late Pliocene to early Pleistocene time. Offset of this unit along the San Andreas Fault is clearly visible on the map around the south end of Upper Crystal Springs Reservoir.
QUATERNARY AND NEOGENE (Quaternary and late Pliocene)	Merced Formation (**QTm**)	Poorly to moderately consolidated, thick-bedded to massive, marine sandstone and siltstone. Beds are cross-bedded and contain scattered layers of rounded pebbles or shell fragments. Thickness ranges from 30 m (100 ft) to possibly more than 91 m (300 ft). In the managed area of the park, the Merced Formation forms cliffs at Fort Funston and Mussel Rock.	**Cenozoic Rocks and Deposits—QTm** is the contemporaneous marine equivalent of the terrestrial Santa Clara Formation (**QTsc**). The Merced Formation likely accumulated in a gap that opened up behind a northwardly migrating right bend in the San Andreas Fault. **QTm** represents shallow-marine nearshore and backshore deposits alternating with terrestrial beach dune and shore deposits. **Faults—QTm** has been uplifted and thrust over the younger Colma Formation (**Qc**) by movement along the Serra Fault. Uplift is evident at Fort Funston. **Paleontological Resources—QTm** is the most fossiliferous Cenozoic unit in the park. It contains carbonized wood, shell fragments, echinoderms, foraminifera, bison, camels, mammoths, mastodons, horses, ground sloths, marine mammals, birds, plants, and trace fossils. Holotype specimens of *Nucella megastoma* (snail) and *Pinus lawsoniani* (pinecone) were collected from **QTm**. **Coastal Features and Processes—**today, the Merced Formation forms coastal bluffs.	**Paleontological Resource Inventory, Monitoring, and Protection—**threats to paleontological resources in the park include unauthorized collecting, vandalism, and erosion. **Slope Movement Hazards and Risks—**coastal areas underlain by **QTm**, for example at Fort Funston, are prone to failure where waves erode steep cliffs and undercut slopes.	**Evolution of the Modern Landscape—**640,000-year-old sediments of the Merced Formation mark the initiation of the modern Sacrament/San Joaquin River system flowing all the way to the ocean. Prior to this, it emptied into a large, land-locked lake in the Central Valley. Offset of this unit along the San Andreas Fault is clearly visible on the map. North of the Golden Gate it is on the west side of the fault; south of the Golden Gate it is to the east.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
NEOGENE (Pliocene and Miocene)	Purisima Formation (**Tps**)	Highly fractured, well indurated mudstone, siltstone, and sandstone. Also includes some chert and volcanic ash. Thickness is at least a few hundred feet but may be as much as 490 m (1,600 ft). **Tps** is only mapped west of the San Andreas Fault. It is not within the managed area of the park. **Tps** forms coastal bluffs near Half Moon Bay.	**Cenozoic Rocks and Deposits—Tps** accumulated in a local basin, which formed as basement blocks shifted due to the tectonic transition from subduction to transform movement. **Tps** is part of a continuous Paleogene marine mudstone and sandstone sequence which also includes **Tm**, **Tsm**, and **Tsc** (mapped on Point Reyes). **Paleontological Resources—Tps** deposits on the Marin Peninsula contain diatoms and cetacean bones. Lithic arkose interbeds are commonly bioturbated. South of Golden Gate, **Tps** deposits contain fossiliferous mudstone beds. Holotype specimen of *Spisula mossbeachensis* (clam) was collected from **Tps**. **Coastal Features and Processes—**today, **Tps** forms coastal bluffs and may be exposed on wave-cut platforms at low tide.	**Slope Movement Hazards and Risks—**coastal areas underlain by **Tps**, such as Seal Cove, are prone to failure where waves erode steep cliffs and undercut slopes. **Paleontological Resource Inventory, Monitoring, and Protection—**threats to paleontological resources in the park include unauthorized collecting, vandalism, and erosion.	**Evolution of the Modern Landscape—Tps** originated to the south and was transported north by movement along the San Andreas Fault. The Purisima Formation records deposition in a shrinking shallow sea. Rocks record shift from deeper off-shore conditions (quiet water) to shallower nearshore conditions (high-energy rivers dumping into estuaries and bays).
PALEOGENE (middle and lower Eocene)	Butano Sandstone (**Tb**)	Thin to thick bedded, arkosic sandstone interbedded with mudstone and shale. Conglomerate, containing well-rounded cobbles and pebbles, is present in lower part of section. Thickness is about 3,000 m (9,800 ft). **Tb** is only mapped west of the San Andreas Fault. In the managed area of the park, it underlies the Phleger Estate. *Note*: GRI GIS data do not show this unit in the park, but recent studies indicate that it, rather than the Whiskey Hill Formation, likely underlies the Phleger Estate (Russel Graymer, US Geological Survey, research geologist, email communication, 3 December 2015).	**Cenozoic Rocks and Deposits—Tb** accumulated in a local basin, which formed as basement blocks shifted due to the tectonic transition from subduction to transform movement. The Butano Sandstone represents submarine fan deposits.	None documented.	**Franciscan Foundation—**most of the Paleocene rocks in the region (**Tw**, **Tb**, **Tsu**, and **Tsl**) are turbidites composed of weathered Franciscan material deposited on top of Salinian or Franciscan basement rocks in deep water. **Development of the San Andreas Fault System—Tb** originated to the south and was transported north by movement along the San Andreas Fault.
PALEOGENE (middle and lower Eocene)	Whiskey Hill Formation (**Tw**)	Arkosic sandstone with silty claystone, glauconitic sandstone, and tuffaceous siltstone. The sandstone beds are well cemented with calcite. Thickness is as much as 900 m (2,900 ft). The GRI GIS data show a large area of **Tw** on the west side of the San Andreas Fault over the Phleger Estate. New information indicates this area is likely the Butano Sandstone. The Whiskey Hill Formation likely only occurs east of the fault.	**Cenozoic Rocks and Deposits—Tw** accumulated in a local basin, which formed as basement blocks shifted due to the tectonic transition from subduction to transform movement. The Whiskey Hill Formation represents bathyal turbidity currents and submarine slumps.	None documented.	**Franciscan Foundation—**most of the Paleocene rocks in the region (**Tw**, **Tb**, **Tsu**, and **Tsl**) are turbidites composed of weathered Franciscan material deposited on top of Salinian or Franciscan basement rocks in deep water.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
PALEOGENE (Paleocene)	Sandstone, shale, and conglomerate – upper part (**Tsu**)	**Tsu** is a very well indurated, soft to hard, sandstone and pebble to cobble conglomerate, with lesser amounts of siltstone, claystone, and carbonate beds, all containing granitic debris. Bedding in **Tsu** is distinct and ranges from thin to massive. Thickness is between 400 m (1,300 ft) and 450 m (1,475 ft). Excellent exposures of **Tsu** occur at Point San Pedro.	**Cenozoic Rocks and Deposits—**the oldest Cenozoic rocks are two Paleocene turbidite deposits (**Tsu**, **Tsl**). **Folds—**near Point San Pedro, **Tsu** is folded into anticlines, synclines, and overturned synclines which parallel the ridges and valleys in the area. **Paleontological Resources—**contains *Turritella pachecoensis* fossils (high-spired snail shells) that suggest an age between about 62 million and 56 million years ago (in California, this period is sometimes called the "Ynezian stage"; Morgan 1981). Holotype specimen of a *Campanile greenellum* (snail) was collected from **Tsu** or **Tsl**. **Coastal Features and Processes—**today, **Tsu** forms coastal bluffs.	**Slope Movement Hazards and Risks—**coastal areas underlain by **Tsu**, for example at Point San Pedro, are prone to failure where waves erode steep cliffs and undercut slopes. **Paleontological Resource Inventory, Monitoring, and Protection—**threats to paleontological resources in the park include unauthorized collecting, vandalism, and erosion.	**Franciscan Foundation—**most of the Paleocene rocks in the region (**Tw**, **Tb**, **Tsu**, and **Tsl**) are turbidites composed of weathered Franciscan material deposited on top of Salinian or Franciscan basement rocks in deep water. **Development of the San Andreas Fault System—Tsu** is mapped only on the west side of the San Andreas Fault and reflects late phases of subduction tectonics to the south. It formed before the development of the San Andreas Fault and was subsequently transported to its current location.
PALEOGENE (Paleocene)	Sandstone, shale, and conglomerate – lower part (**Tsl**)	**Tsl** is a laminated to rhythmically bedded, soft to medium hard, brown, fine to coarse grained, thin bedded, arkosic turbidite sandstone and black shale. The base of **Tsl** is not exposed, but thickness is estimated between 450 m (1,475 ft) and 760 m (2,500 ft). Excellent exposures of **Tsl** occur at Point San Pedro.	**Cenozoic Rocks and Deposits—**the oldest Cenozoic rocks are two Paleocene turbidite deposits (**Tsu**, **Tsl**). **Tsu** unconformably overlies Salinian granite. **Paleontological Resources—**contains *Turritella pachecoensis* fossils (high-spired snail shells) that suggest an age between about 62 million and 56 million years ago (in California, this period is sometimes called the "Ynezian stage";Morgan 1981). Holotype specimen of a *Campanile greenellum* (snail) was collected from **Tsu** or **Tsl**. **Coastal Features and Processes—**today, **Tsl** forms coastal bluffs.	**Slope Movement Hazards and Risks—**coastal areas underlain by **Tsl**, for example at Point San Pedro, are prone to failure where waves erode steep cliffs and undercut slopes. **Paleontological Resource Inventory, Monitoring, and Protection—**threats to paleontological resources in the parks include unauthorized collecting, vandalism, and erosion.	**Franciscan Foundation—**most of the Paleocene rocks in the region (**Tw**, **Tb**, **Tsu**, and **Tsl**) are turbidites composed of weathered Franciscan material deposited on top of Salinian or Franciscan basement rocks in deep water. **Development of the San Andreas Fault System—Tsl** is mapped only on the west side of the San Andreas Fault and reflects late phases of subduction tectonics to the south. . It formed before the development of the San Andreas Fault and was subsequently transported to its current location.
CRETACEOUS	Granitic rocks of Montara Mountain (**Kgr**)	Very light gray to light brown, medium to coarse grained quartz diorite with some granite; contains abundant hornblende and biotite. Aplite, pegmatite, and rhyolite dikes are also present. **Kgr** rocks are highly fractured and deeply weathered. Jointing is common and best seen in sea cliffs. Exposures of hard, unfractured rock are rare. **Kgr** only occurs west of the San Andreas Fault and south of the Golden Gate. **Kgr** forms the bedrock under Corral de Tierra and is mapped at the surface along ridges. These are the only Salinian basement rocks mapped within the park. The other Salinian units (**Kg**, **Kgri**, and **Kgdt**) are mapped in Point Reyes, north of the Golden Gate.	**Rocks of the Salinian Complex—**intrusive igneous rocks, such as **Kgr**, originated to the south in association with the batholith that formed a volcanic arc during Franciscan subduction. Kgr was later sliced off and transported north to its present location along the San Andreas Fault. Salinian igneous rocks are strikingly different from Franciscan Complex rocks. **Slope Movements—**the southwest flank of Montara Mountain is pockmarked by numerous small, shallow landslides in **Kgr** and in grus (weathered granite). **Coastal Features and Processes—Kgr** weathers to produce beach sands.	**Slope Movements Hazards and Risks—**shallow landslides may occur in areas of grus associated with map unit **Kgr** on Montara Mountain. **Abandoned Mineral Lands**—a borrow pit of weathered **Kgr** occurs in Corral de Tierra.	**Franciscan Foundation—**granitic rocks of Montara Mountain are derived from a batholith in southern California that fueled the Sierran arc during Franciscan subduction. **Evolution of the Modern Landscape—**movement along the San Andreas Fault sliced off and carried a section of **Kgr** roughly 310 km (193 mi) north to its present location.
CRETACEOUS	Gabbro and diabase (**Kgd**)	Coarse to fine grained, equigranular to porphyritic igneous rock. Intrusive into the Franciscan Complex; occurs as segregations in serpentinite (**KJfsu**). Weathered **Kgd** rock is speckled brown and orange and ranges from crumbly to moderately hard. **Kgd** is not mapped within the managed area of the park. Within the authorized boundary, **Kgd** is only mapped on Angel Island where it occurs as small bodies within serpentinite (**KJfsu**).	None documented.	None documented.	**Franciscan Foundation—**non-Franciscan gabbro and diabase (**Kgd**) intruded the Franciscan Complex on Angel Island.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
JURASSIC AND CRETACEOUS	**FRANCISCAN COMPLEX** Basalt and Greenstone (**Kfg**, **KJfg**, **KJfgs**)	This group of units consists mainly of basalt and greenstone with lesser amounts of diabase and rare gabbro. Nearly all of the basalt in the park has been altered to some extent and can also be referred to as greenstone; the names are typically used interchangeably. Gabbro and diabase have a similar chemical composition to basalt but differ in texture (crystal size). Fresh rock is structureless to strongly pillowed. Flows, breccia, and tuff are less common. Chert and/or limestone interlayers occur locally (too small to show on map). Good exposures of pillow basalt (**Kfg**) occur at Point Bonita in the Marin Headlands. **KJfg** is mapped extensively on the Pilarcitos fault block south of San Francisco and west of the San Andreas Fault. Within the managed area of the park, **KJfg** is mapped in the southeastern Marin Headlands, at Mori Point, and on Sweeney Ridge. **KJfgs** is mapped primarily in the western Marin Headlands.	**Rocks of the Franciscan Complex—**basalt and greenstone form the base of the Franciscan sequence. **Franciscan Terranes—**the Nicasio Reservoir terrane is primarily basalt and gabbro. Franciscan basalt and greenstone units are also mapped in the Marin Headlands and Permanente terranes. **San Andreas Fault System—**Franciscan rocks are primarily east of the San Andreas fault, except on the Pilarcitos fault block where **KJfm**, **KJfl**, **KJfss**, **KJfmss**, and **KJfg** are mapped west of the San Andreas Fault. **Coastal Features and Processes—**today, Franciscan basalt and greenstone form cliffs along coast. **Sea Caves—**most common in these harder rocks of the Franciscan Complex rather than in the softer Cenozoic sedimentary rocks.	**Slope Movements Hazards and Risks—**where sheared serpentinite occurs or hydrothermal alteration has produced soft clays, erosion has produced a subdued, hilly topography, which is prone to landslides. **Sea Cave Documentation and Management—**sea caves may be present in basalt and greenstone of the Franciscan Complex. **Abandoned Mineral Lands**—the managed area of the park contains two former quarries mapped in basalt and greenstone; one is at Mori Point and the other is in the Marin Headlands.	**Franciscan Foundation—**basalt and greenstone of the Franciscan Complex began forming at a mid-ocean ridge roughly 200 million years ago. They traveled with the Farallon plate and accreted to North America episodically from 160 million to 50 million years ago.
CRETACEOUS	**FRANCISCAN COMPLEX** Diabase (**Kfdb**)	Porphyritic, mafic dike rock. Thought to be a fragment of a sheeted dike complex. **Kfdb** is only mapped on Point Bonita in the Marin Headlands.	**Rocks of the Franciscan Complex—**subvolcanic (formed at shallow depths) diabase dikes are associated with the basalt and greenstone base of the Franciscan sequence. **Franciscan Terranes—Kfdb** at Point Bonita is part of the Permanente terrane. This youngest Franciscan terrane was originally deposited in association with seamounts near the equator. **Coastal Features and Processes—**today, **Kfdb** forms cliffs at Point Bonita.	**Sea Cave Documentation and Management—**sea caves may be present in diabase of the Franciscan Complex.	**Franciscan Foundation—**diabase likely formed at shallow depths below basalt and greenstone.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
JURASSIC AND CRETACEOUS	**FRANCISCAN COMPLEX** Chert and Limestone (**Kfl**, **KJfc**, **KJfl**, **KJfbch**)	This group of units is primarily chert and limestone with lesser amounts of shale, some quartz veins, and clay minerals. The limestone is light-gray, hard, dense, and finely crystalline. It is massive in some places and in other places it is distinctly bedded between layers of black chert. The chert is of radiolarian origin and may be black, white, red, green, orange, brown, or gray. The chert is hard and brittle and most commonly in the form of "ribbon chert" where it is interbedded with thin shale layers. Alternatively, chert occasionally forms in very thick layers. The chert in some of these thick exposures has been recrystallized and cut by crystalline quartz veins. Along faults the chert has been hydrothermally altered into tan to buff clay minerals. Chert is also commonly interlayered with or surrounded by greenstone of the Franciscan Complex. Chert is abundant within the managed area of the park, especially on the Marin Headlands where chert forms ridges. Exceptional exposures of ribbon chert are along Conzelman Road. Limestone is less common; **Kfl** is restricted to two small masses in the San Andreas Fault system between Olema and Bolinas. Map unit **KJfl** is mapped near Mori Point; most of it is not within NPS-managed lands.	**Rocks of the Franciscan Complex—**chert and limestone form the middle of the Franciscan sequence. **Franciscan Terranes—**Franciscan chert makes up about 1/3–1/2 of the Marine Headlands terrane. Chert and limestone units are also mapped in the Permanente terrane. The Permanente chert was originally deposited in association with seamounts near the equator. **Faults—**a large fault-bounded block of **KJfbch** surrounded by mélange (**KJfm**) occurs at the eastern edge of Muir Woods National Monument. **Paleontological Resources—**chert is composed of the shells of microscopic radiolarians, and limestone contains the fossil shells of foraminifera. **Coastal Features and Processes**—today, Franciscan chert and limestone form cliffs along the coast. **Sea Caves—**sea caves form most commonly in harder rocks (e.g., chert) of the Franciscan Complex rather than in the softer Cenozoic sedimentary rocks; limestone dissolution may contribute to sea cave formation.	**Sea Cave Documentation and Management—** undocumented sea caves may be present in chert and limestone of the Franciscan Complex. **Paleontological Resource Inventory, Monitoring, and Protection—**threats to paleontological resources in the park include vandalism and erosion. Unauthorized collection is not a major threat in these rocks because of the abundance of fossils and difficulty in extraction. **Abandoned Mineral Lands**—the managed area of the park contains two former quarries mapped in chert, both are located in the Marin Headlands.	**Franciscan Foundation—**chert and limestone accumulated on top of basalt and greenstone in a tropical open ocean environment near the equator beginning about 200 million years ago. They traveled with the Farallon plate and accreted to North America episodically from 160 million to 50 million years ago.
JURASSIC AND CRETACEOUS	**FRANCISCAN COMPLEX** Graywacke and shale (**Kfgwy**, **KJfss**, **KJfmss**, **KJfsh**, **KJfbss**)	This group of units is primarily graywacke sandstone and shale with lesser amounts of conglomerate and metagraywacke. Graywacke is interbedded with thin layers (5–13 cm [2–5 in]) of fissile, generally dark-gray shale and some thick conglomerate lenses. Graywacke may be as much as 300 m (984 ft) thick. Graywacke and shale are extensively mapped in the managed area of the park. These rocks are mapped over most of Sweeney Ridge, the north end of Ocean Beach, and at Fort Mason; as well as at the Presidio, on Alcatraz, at Stinson Beach, on Bolinas Ridge, and throughout the Marin Headlands.	**Rocks of the Franciscan Complex—**graywacke and shale are the most abundant rocks in the Franciscan Complex; they form the top of the Franciscan sequence. **Franciscan Terranes—**graywacke and shale are present in most of the terranes in the park. The Alcatraz, Novato Quarry, and San Bruno Mountain terranes are all characterized by graywacke sandstone and shale turbidite deposits. Graywacke and shale are also mapped in the Marin Headlands and Permanente terranes. **Slope Movements—**graywacke and shale of the Franciscan Complex formed as a result of ancient slope movements; turbidity currents carried sediments down the steep continental slope. **Paleontological Resources**—macrofossils are rare in Franciscan rocks. Four bivalves (two of which are newly described species) and one gastropod were documented on Alcatraz; two ammonites, one gastropod, and one belemnite fossil were discovered in the Marin Headlands; one ammonite was documented from the Marin Headlands terrane in San Francisco. **Coastal Features and Processes**—today, Franciscan graywacke and shale form cliffs along the coast. **Sea Caves—**sea caves form most commonly in hard rocks of the Franciscan Complex rather than in the softer Cenozoic sedimentary rocks.	**Slope Movement Hazards and Risks—**graywacke in Marin County weathers to produce vermiculite (swelling clays), which make them more susceptible to landslides than their counterparts north of Marin County (not on the GRI map). **Sea Cave Documentation and Management—** undocumented sea caves may be present in graywacke and shale of the Franciscan Complex. **Paleontological Resource Inventory, Monitoring, and Protection—**threats to paleontological resources in the park include unauthorized collecting, vandalism, and erosion.	**Franciscan Foundation—**graywacke and shale were deposited on top of chert and limestone by turbidity currents in the deep oceanic trench of the Franciscan subduction zone around 100 million years ago.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
JURASSIC AND CRETACEOUS	**FRANCISCAN COMPLEX** Serpentinite (**KJfsu**)	Greenish gray serpentinite and small amounts of ultramafic rocks (e.g., gabbro and diabase). Occurs as lenses and irregularly shaped masses. Soft and sheared serpentinite encloses blocks (commonly less than 3 m [10 ft] in diameter) of hard and unsheared serpentinite and silica carbonate rocks (**KJfbsc**). Within the managed area of the park, serpentinite is mapped at Land's End, Baker Beach, Fort Point, the Presidio, Stinson Beach, and the Marin Headlands.	**Franciscan Mélange—KJfsu** is found within and along the boundaries of the Franciscan Mélange. **Coastal Features and Processes—KJfsu** tends to form sea cliffs where mapped along the coast. **Sea Caves—**sea caves form most commonly in the hard rocks of the Franciscan Complex rather than in the softer Cenozoic sedimentary rocks.	**Slope Movement Hazards and Risks—**weak and highly fractured rocks, like serpentinite, are the most susceptible to landslides. **Disturbed Land Restoration—**in 2002, the Geologic Resources Division recommended stabilization and waste removal at the serpentinite cliffs of Baker Beach. **Coastal Serpentine Scrub Preservation—**serpentinite produces serpentine soils that are associated with rare and endemic plant communities. Mapped serpentinite can be used to locate potential serpentine scrub communities. **Naturally Occurring Hazardous Materials—**asbestos—a known carcinogen—may naturally occur in serpentinite. Health hazards arise when activities that disturb asbestos-containing rocks and soil generate asbestos-laden dust that may be inhaled.	**Franciscan Foundation—**serpentinite likely originated as peridotite in the Coast Range ophiolite (Jurassic ocean crust that was emplaced within the continent before accretion of the Franciscan Complex). The peridotite was likely metamorphosed to serpentinite in the subduction zone and later faulted into the Franciscan Complex.
JURASSIC AND CRETACEOUS	**FRANCISCAN COMPLEX** High grade metamorphic rocks (**KJfsch**, **KJfbm**, **KJfbmg**, **KJfmgs**)	Most Franciscan rocks are weakly metamorphosed. This category separates out the units that contain high grade metamorphic rocks, which are indicated by the presence of blueschist minerals (e.g., glaucophane and lawsonite), amphibolite, or eclogite. Chunks of these rocks are often found "floating" in the mélange of the Franciscan Complex or surrounded by serpentinite. Areas of high grade metamorphic rock are uncommon, therefore many occurrences are represented by point features (see "Mélange blocks" in the GRI GIS data). **KJfbmg** blocks are mapped within the managed area of the park near Tennessee Valley and Muir Beach. A block of **KJfmgs** is mapped in Muir Woods National Monument.	**Franciscan Terranes—**metamorphic rocks are common in the Yolla Bolly terrane, the oldest and easternmost Franciscan terrane in the park. **Franciscan Mélange—KJfbm** and **KJfmgs** are found as blocks in Franciscan mélange (point features in GRI GIS data). **Slope Movements—KJfsch (**graywacke) formed as a result of ancient underwater slope movements that generated turbidity currents.	None documented.	**Franciscan Foundation—**high grade metamorphic rocks formed during the earliest stages of Franciscan subduction. They were later brought to the surface along faults associated with accretion.
JURASSIC AND CRETACEOUS	**FRANCISCAN COMPLEX** Silica carbonate rocks (**KJfbsc**)	Reddish brown, hydrothermally altered serpentinite (e.g., chalcedony, opal, quartz) along the margins of serpentinite (**KJfsu**) and in severely sheared mélange (**KJfm**). May contain minor cinnabar. Within the managed area of the park, silica carbonate rocks are mapped at Stinson Beach.	**Rocks of the Franciscan Complex—KJfbsc** occurs in hydrothermal areas, mainly near the north end of Bolinas Ridge, and in fissures along the margins of **KJfsu** (serpentinite).	**Naturally Occurring Hazardous Materials—**mercury occurs in the mineral cinnabar, which occurs in **KJfbsc** in very small amounts; it is not likely a health issue at the park.	**Franciscan Foundation—**silica carbonate rocks formed in shear zones during and after accretion of the Franciscan Complex to North America. **Development of the San Andreas Fault System—**some parts of the unit may be Tertiary in age where it is related to volcanism associated with the growth of the San Andreas Fault.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
JURASSIC AND CRETACEOUS	**FRANCISCAN COMPLEX** Mélange (**KJfm**)	A chaotic mixture of fragmented Franciscan rocks in an extensively sheared shale and sandstone matrix. Tectonic inclusions are largely of greenstone, chert, graywacke, and their metamorphosed equivalents, plus exotic high grade metamorphic rocks and serpentinite. Includes minor discrete masses of limestone too small to be mapped. Dark gray where fresh, yellowish brown where weathered and in places is eroded to form badlands topography. Within the managed areas of the park, mélange is abundant; it is mapped in the South Coastal Bluffs, Ocean Beach/Fort Funston, Stinson Beach, Homestead Valley, Dias Ridge, Muir Beach, Muir Woods, and Marin Headlands areas.	**Franciscan Terranes—KJfm** makes up the wide areas of mélange, sometimes called the "Central terrane," which separates the different Franciscan terranes. Mélange is also abundant within the Marin Headlands terrane. **Faults—**faults typically surround large blocks (as much as several kilometers long) of other Franciscan rocks set among mélange. **Geothermal Systems and Hydrothermal Features—** the hot spring near Steep Ravine beach is mapped in **KJfm**. **Paleontological Resources—**two bivalve specimens are reported from **KJfm** in the park.	**Slope Movement Hazards and Risks—**weak and highly fractured rocks, like mélange, are the most susceptible to landslides. **Sea Cave Documentation and Management—**sea caves may be present in mélange of the Franciscan Complex. **Paleontological Resource Inventory, Monitoring, and Protection—**threats to paleontological resources in the park include unauthorized collecting, vandalism, and erosion.	**Franciscan Foundation—**mélange formed between the Franciscan terranes during accretion to the North American continent 160 million to 50 million years ago.
JURASSIC (?)	Siliceous volcanic rocks and keratophyre (**Jsv**)	Highly altered silicic volcanic (formed at the surface) and subvolcanic (formed at shallow depths) rocks. Feldspars are almost all replaced by albite. **Jsv** is mapped west of Upper Crystal Springs Reservoir on the Pilarcitos fault block; not within the managed area of the park.	**Ancient Convergent Boundary—Jsv** probably originated as oceanic crust at a mid-ocean ridge and was subsequently emplaced on the continent in association with the Franciscan subduction zone; it may be part of the Coast Range ophiolite. **San Andreas Fault System—Jsv** is part of the "Franciscan" basement which occurs west of the San Andreas Fault within the Pilarcitos fault block; all other rocks west of the fault are Salinian Complex rocks or younger.	None documented.	**Franciscan Foundation—Jsv** probably represents Jurassic ocean crust which became trapped in the forearc basin as the subduction zone was coming together. Timing was before the accretion of the Franciscan Complex. It may be part of the Coast Range ophiolite. The Jurassic age assignment for these rocks is based on analyses of similar rocks in Alameda and Contra Costa counties.
JURASSIC (?)	Gabbro (**Jgb**)	Light greenish gray, dark-gray weathered, mafic intrusive rock. Mostly gabbro but also includes some diabase locally. **Jgb** is mapped west of Upper Crystal Springs Reservoir on the Pilarcitos fault block; not within the managed area of the park.	**Ancient Convergent Boundary—Jgb** probably originated as oceanic crust at a mid-ocean ridge and was subsequently emplaced on the continent in association with the Franciscan subduction zone; it may be part of the Coast Range ophiolite. **San Andreas Fault System—Jgb** is part of the "Franciscan" basement, which occurs west of the San Andreas Fault within the Pilarcitos fault block; all other rocks west of the fault are Salinian Complex rocks or younger.	None documented.	**Franciscan Foundation—Jgb** probably represents Jurassic ocean crust which became trapped in the forearc basin as the subduction zone was coming together. Timing was before the accretion of the Franciscan Complex. The age of this unit is unknown, but it is probably part of the Jurassic Coast Range Ophiolite.