National Park Service
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Natural Resource Stewardship and Science

Point Reyes National Seashore

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2018/1784

ON THE COVER
The southwest view from Mount Vision on Inverness Ridge includes Drakes Estero, the Point Reyes Headlands, and the Pacific Ocean beyond. NPS photograph by Rebecca Port (Geologic Resources Division).
THIS PAGE
The valley occupied by Tomales Bay, which separates Point Reyes from the mainland, was formed by the San Andreas Fault. NPS photograph by Rebecca Port (Geologic Resources Division), taken facing southeast from Pierce Point Road on Tomales Point.

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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 (https://www.nps.gov/im/publication-series.htm). If you have difficulty accessing information in this publication, particularly if using assistive technology, please email irma@nps.gov

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Executive Summary

The Geologic Resources Inventory (GRI) provides geologic map data and pertinent geologic information to support resource management and science-informed decision making in more than 270 natural resource parks throughout the National Park System. The GRI is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division (GRD) of the NPS Natural Resource Stewardship and Science Directorate administers the GRI.

This report synthesizes discussions from a scoping meeting held in 2007 and a follow-up conference call in 2016 (see Appendix A). Chapters of this report discuss the geologic setting, distinctive geologic features and processes within Point Reyes National Seashore, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the previously completed GRI geologic map data. A poster (in pocket) illustrates these data.

Point Reyes National Seashore stands in stark contrast to the surrounding California mainland as a kind of "geologic island." Arguably one of the most geologically active parks in the national park system, the entire peninsula was transported along faults to its current location and continues to move northwest to this day along the San Andreas Fault. Earthquakes are frequent and the park is the location of the maximum known movement [6 m (20 ft)] on the San Andreas Fault during the 1906 earthquake.

The GRI geologic map data cover the area of the park, Golden Gate National Recreation Area, Muir Woods National Monument, Fort Point National Historic Site, and much of San Francisco. The data is available for download in a Geographic Information System (GIS) format at the GRI publications website: http://go.nps.gov/gripubs. A component dataset limited to the Marin Headlands and Point Reyes areas is also available for download at the GRI publications website. Mapping by the California Geological Survey (Wagner et al. 2006) and the United States Geological Survey (USGS) (Schlocker et al. 1958; Pampeyan 1994; Clark and Brabb 1997; Bonilla 1998; Blake et al. 2000; Brabb et al. 2000) served as the sources for the GRI GIS data. While the area covered by the GRI GIS data far exceeds the park's boundary, this report will be limited to the geologic units and features mapped within Point Reyes National Seashore's authorized boundary except where external units and features may affect geologic resource management. For geologic information regarding the north district of Golden Gate National Recreation Area, refer to the GRI report for Golden Gate NRA (Port 2016).

Geologic features and processes include the following:

- **Cretaceous Granitic Rocks**. The Salinian structural block is west of the San Andreas Fault and underlies all of Point Reyes National Seashore. This block is composed of Late Cretaceous (100.5 million to 66.0 million years old) plutonic igneous rocks, primarily granodiorite and tonalite. In most places Salinian rocks are covered by younger rocks and sediments, however, prominent exposures occur in the park on the Point Reyes Headlands and Inverness Ridge. These rocks originated from a massive batholith in Southern California that formed in association with the Franciscan subduction zone. Lateral fault displacement transported the rocks to their current location.
- **Tertiary Marine Rocks**. Sedimentary marine rocks cover the majority of the geologic map of the park. These rocks record changes in sea level over the past roughly 56 million years. Tertiary marine rocks include mudstone, sandstone, and conglomerate which represent deep water, nearshore, and coastal deposition, respectively. Underwater landslide deposits, called turbidites, from off the edge of the steep continental shelf are common in some units. Fossils are also common in some units.
- **Quaternary Sediments**. Quaternary sediments accumulated during the last 2.58 million years. All of these deposits are products of processes still active in the park today. Quaternary sediments in the park include bay mud, beach sand, marine and stream terrace deposits, stream channel deposits, alluvium, dune sand, and landslide deposits.
- **Franciscan Complex**. The Franciscan Complex makes up the basement east of the San Andreas Fault. With few exceptions, these rocks do not occur within Point Reyes National Seashore, but do underlie most

of Golden Gate National Recreation Area. Rocks of the Franciscan Complex formed or accumulated in an ancient subduction zone from about 160 million to 50 million years ago. Franciscan Complex rocks include basalt, greenstone, chert, limestone, graywacke, shale, and serpentinite.

- **Type Sections**. The type section of a rock formation displays the rocks so well that it is used as a reference for all other occurrences of that particular sequence of rocks. The type section is often the location where scientists first described the formation. Type sections are popular stops on field trips. Two type sections occur in the park and two more occur in neighboring Golden Gate National Recreation Area.
- **Folds**. Folds are bends in originally flat rock strata. The GRI GIS data identified 11 folds in Point Reyes National Seashore. The largest fold, referred to informally as the Point Reyes syncline, defines the overall geologic structure of the park. The axis of this fold extends northwest along the west shore of Drakes Estero. The remaining folds may reflect blind (buried) faults in the underlying Salinian basement rocks.
- **Faults**. The Point Reyes Peninsula is bound to the east by the transform San Andreas Fault and to the south and west by the Point Reyes Fault. The San Andreas Fault is moving the park northward relative to the California mainland by about 17 to 30 mm (0.7 to 1.2 in) per year and the Point Reyes Fault is raising the peninsula about 1 mm (0.04 in) per year. The GRI GIS data identified 11 other smaller faults in the park.
- **Earthquakes**. Earthquakes occur every day in the San Francisco Bay Area, though the vast majority are not strong enough to be felt or cause damage. Historically significant earthquakes that shook the park include the 1868 Hayward Fault, 1906 San Francisco, 1989 Loma Prieta, and 2014 South Napa earthquakes. Point Reyes National Seashore is a classic place to see the effects of the 1906 earthquake where the ground ruptured and the peninsula lurched nearly 6 m (20 ft) in less than a minute. The earthquake trail at the Bear Valley Visitor Center interprets the 1906 earthquake.
- **Landslides**. The term "landslide" is applied to a variety of downslope movements of rock, regolith, and /or soil. Areas of weak rocks and steep slopes are most susceptible to landslides. In the park, rockfall, bluff failures, and slumps are common along coastal cliffs, and debris flows may occur in valleys following heavy rain. A large area of active coastal landslides extending inland several kilometers (several miles) occurs in the area of Double Point. Most of the slides in this region occur with the Santa Cruz Mudstone.
- **Lacustrine Features**. The natural lakes that occur in the park were created from geologic processes. For example, sag ponds formed where streams impounded by fault movements caused water to collect in depressed areas along the San Andreas Fault. Sag ponds are a common topographic feature of faulted landscapes and the park contains many small sag ponds. Natural lakes also formed in association with landslides. Water filled the depressions created behind slumped blocks of Santa Cruz Mudstone. In addition to natural lakes, farmers and ranchers created a hundred or more stock ponds in the park by damming streams.
- **Coastal Resources**. The coast in the park varies from cliffs and bluffs, to sandy beaches and dunes, to bays, estuaries, and lagoons. Cliffs and bluffs are typically composed of Salinian basement and Tertiary marine rocks, while beaches and coastal water bodies are comprised of, or underlain by Quaternary sediments. Natural processes affecting coastal environments include landslides, longshore drift, eolian (wind) processes, and tides.
- **Marine Resources**. Marine resources in the park include the submerged processes and features that occur within 1 mile of the shore (the extent of the park boundary). A significant marine process in the park is upwelling, where nutrient rich water rises to the surface and forms the basis for a complex food web. Submerged features include benthic habitats and seafloor geology. This information is not included in the GRI GIS data; however, the USGS California Seafloor Mapping Program produced a series of maps for the offshore areas surrounding Point Reyes National Seashore.
- **Paleontological Resources**. The park contains considerable paleontological resources and the potential exists for continued discovery. Documented fossils include marine vertebrates (whales, dolphins, sharks), marine invertebrate (snails, clams, crustaceans, echinoderms), microfossils (diatoms, radiolarians, foraminifera), and plants (pollen, wood, pine cones). A paleontological resource inventory for the park has not yet been completed.
- **Sea Caves**. Sea caves are common features along the rocky coastline of the park. They form where 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. All of the known caves in the park are sea caves, though the number of caves is not known. Sea caves provided habitat to a variety of marine life.
- **Geothermal Features and Processes**. There is some evidence of geothermal activity in the park. Deep

faults probably provide conduits for hydrothermal waters. For instance, the Palomarin area hosts sulfur seeps and oil and gas seeps occur in the vicinity of Duxbury Point.

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

- **Earthquakes**. Probabilities for a strong earthquake in or near the park within the next 30 years are between 0.30 and 0.50 (30% to 50% "chance"). Earthquakes cannot be prevented and prediction is imprecise; therefore, preparedness is imperative to minimize risk associated with earthquake hazards. Many organizations, such as the California Geological Survey, and resources, such as the park's emergency response plan, are available to assist park staff with earthquake preparation and planning.
- **Landslide Hazards**. Landslides are natural elements of landscape change. Landslides are a geologic hazard where they impact park resources, infrastructure, or visitor safety, such as when visitors hike near cliffs or in quarries. Alerting visitors to the hazards and risks associated with landslides is a first step toward reducing the risk. Determining landslide susceptibility and responding to hazards can be accomplished through field observations, landslide maps, and/or photographic monitoring. Maps to assist with landslide hazard mitigation are available from the USGS and California Geological Survey.
- **Flooding**. Flooding occurs in the park following winter storms and as a result of El Niño events and King Tides. Flooding can impact roads, trails, and beaches. Coastal flooding is a concern because the shoreline is a popular destination for park visitors. To assist with assessing flood potential, park managers may choose to monitor fluvial geomorphology in the park.
- **Coastal and Marine Resource Management and Planning**. Coastal and marine resources will be impacted by climate change and sea level rise. The NPS has developed a variety of databases and guidance for managing coastal resources and planning for the impacts of climate change, including a coastal adaptation strategies handbook which highlights processes, tools, and examples that are applicable to many types of NPS plans and decisions. The NPS also developed a cultural resources climate change response strategy that connects climate science with historic preservation planning.
- **Paleontological Resource Inventory, Monitoring, and Protection**. All paleontological resources are non-renewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act. Several of the fossil sites in the park are in high-visitation areas and coastal erosion exposes fossiliferous rocks and threatens the long-term stability and condition of fossils. If not already in process, park managers could monitor paleontological resources using the monitoring protocol that was developed in 2016.
- **Sea Cave Inventory and Monitoring**. 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. An official sea cave inventory has not yet been completed for the park. A cave management plan has also not yet been completed. The NPS Geologic Resources Division can facilitate the inventory and development of such a plan.
- **Disturbed Land Restoration**. Much of the land in the park has been altered from its natural state by development and/or agriculture. Only restoration projects with a geologic component are discussed in this report. Projects include watershed and wetlands restoration and dune restoration. Large watershed and wetlands projects include the Giacomini Wetland Restoration Project, the Coastal Watershed Restoration Program, and the Glenbrook Dam Removal Project. Dune restoration projects include a proposal to restore up to 600 acres of coastal dune habitat and a project near Abbott's Lagoon which began in February 2011.
- **Documentation and Reclamation of Abandoned Mineral Lands**. The park contains 47 abandoned mineral land features associated with clay, sand, and gravel quarries. Features include historic lime kilns, surface mines, waste rock, and highwalls. These features pose a variety of resource management issues such as visitor and staff safety and environmental quality of air, water, and soil. As of 2008, park managers had administratively closed the more than 30 borrow pits in the park and plans were in place to restore those that pose safety risks. An accurate inventory of abandoned mineral land features would identify human safety hazards and contamination issues, and facilitate closure, reclamation, and restoration.
- **Conventional Energy and Mineral Development and Extraction**. Non-administrative (not conducted by the park) sand and gravel extraction occurs in the park. These quarries had been administratively closed since the early 1990s, but evidence of continued use was document by NPS staff in some locations. Economic minerals exist in the park but they have never been exploited nor do any plans exist to mine them.

- **Renewable Energy Development**. 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 Golden Gate National Recreation Area. Park managers are concerned about the impacts of proposed tidal, wind, and wave energy projects on the park environment. Further investigation is required to determine if these activities would impact Point Reyes National Seashore.

Products, Acknowledgments, and Abbreviations

The NPS Geologic Resources Division partners with the Colorado State University Department of Geosciences to produce GRI products. The US Geological Survey and California Geological Survey developed the source maps. This chapter describes GRI products and acknowledges contributors to this report. It also includes a list of abbreviations.

GRI Products

The GRI team undertakes three tasks for each park in the Inventory and Monitoring program: (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 non-geoscientists.

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 GIS 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 (this document). The GRI team conducts no new field work in association with their products.

The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (§ 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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List of Abbreviations

- GIS: Geographic Information System
- GRD: Geologic Resources Division
- GRI: Geologic Resources Inventory
- MYA: millions of years ago
- NPS: National Park Service
- NS: National Seashore
- NRA: National Recreation Area
- USGS: United States Geological Survey

Figure 1. Map of Point Reyes National Seashore.
Point Reyes National Seashore includes most of the Point Reyes Peninsula, a roughly triangular-shaped area separated from the California mainland by Tomales Bay, Olema Valley, and Bolinas Lagoon (which were formed by the San Andreas Fault). NPS graphic available at https://www.nps.gov/hfc/cfm/carto.cfm.

Setting and Significance

This section describes the regional setting and significance of Point Reyes National Seashore and summarizes connections among geologic resources, other park resources, and park stories.

Visitors to Point Reyes National Seashore may observe that the park seems "alive" in every sense. Tule elk, grazing cows, California quail, coyotes, and harbor seals are all common visitor sightings. In a single day, strong winds can give way to calm sunshine and then to dense fog. Waves relentlessly crash upon coastal cliffs. And the entire peninsula is moving northwest along faults of the San Andreas system. Sometimes this movement is abrupt, as was the case during the 1906 earthquake when the park leapt 6 m (20 ft) to the northwest on the morning of 18 April. This natural sanctuary is only an hour's drive from Golden Gate Bridge and the populous Bay Area. Because of this accessibility and the variety of natural and cultural resources to explore, the park receives more than 2 million visitors annually.

Creation of Point Reyes National Seashore, herein referred to as the "park," was the result of nearly four decades of local activism and some federal foresight (Lage 2004). On 13 September 1962, President John F. Kennedy signed the bill that authorized the establishment of Point Reyes National Seashore as part of the National Park System (fig. 1). In 1972, President Nixon authorized the funds to purchase the original 21,807 ha (53,884 ac) of land which would become the park. Citizens and local conservation groups banded together in support of a proposal for a wilderness area within the national seashore and in 1985 Congress designated 10,267 ha (25,370 ac) as the Philip Burton Wilderness. Philip Burton was a congressman from San Francisco responsible for more than doubling the wilderness acreage of the National Park System and for the creation of Golden Gate National Recreation Area (Lage 2004). The park is surrounded by the Greater Farallones National Marine Sanctuary which was designated in 1981 and is administered by NOAA (fig. 2).

Geographic Setting

The park boundary roughly coincides with the Point Reyes Peninsula (fig. 1). The peninsula is a triangular-shaped land area in Marin County, California. It is separated from the mainland by Tomales Bay, Olema Valley, and Bolinas Lagoon. The peninsula extends southwest into the Pacific Ocean to an apex—Point Reyes (Clark et al. 1984). Access within the park includes roads, trails, and beaches (fig. 1). Point Reyes National Seashore also administers the north district of Golden Gate National Recreation Area (NRA). Those lands are not discussed in this report; refer to the GRI report for Golden Gate NRA (Port 2016) for more information.

The park is within the California Coast Ranges section of the Pacific Border physiographic province, a long region of lowlands and mountains running along the western coast of the United States (fig. 3). The Coast Ranges are a series of parallel, northwest–southeast oriented ranges separated by valleys and spanning more than 600 km (370 mi) of the California coast. The park is typically cool year-round with dry, foggy summers and rainy winters. A broad range of habitats occur, including ocean, shore, estuary, grassland, and upland forest. Upwelling of nutrient-rich ocean water forms the basis of a food web which, at least in part, supports the ecosystems associated with each of these habitats. The park is known for its biodiversity which includes marine animals such as seals and crabs; coastal plants and animals like eelgrass and shore birds; and upland organisms like reptiles, deer, coyote, elk, and fir and pine trees.

The landscape of the park includes valleys, ridges, rolling grasslands, sandy beaches, and rocky promontories (table 1). Elevations range from sea level to the high point of Mount Wittenberg on Inverness Ridge at 429 m (1,407 ft). The physiography of the landscape is largely controlled by an underlying geologic structure—the Point Reyes syncline (see "Folds" section).

Geologic Setting

Coastal California is one of the most geologically active areas in the country, and Point Reyes National Seashore is no exception. The west coast of North America is an active continental margin, meaning that the edge of the continent coincides with a boundary between tectonic plates (fig. 4). Conversely, the east coast of North America is a passive continental margin; the nearest plate boundary is in the middle of the Atlantic Ocean. 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 in the hot and "soft" rocks of the mantle within the Earth drives movement on the Earth's surface. The rigid surface of the Earth is called the "crust" and is broken up into slabs referred to as tectonic plates. The

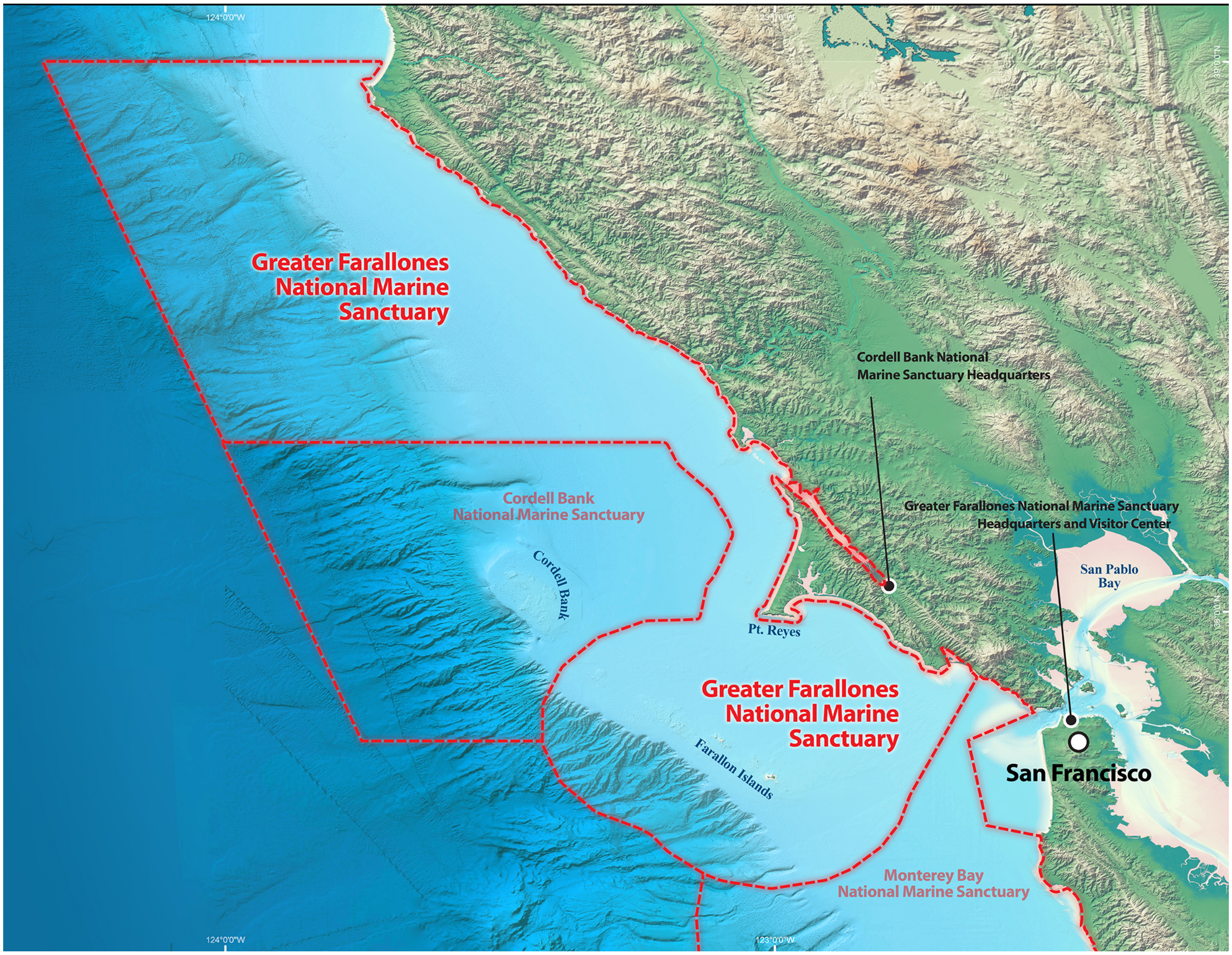


Figure 2. Map of national marine sanctuaries surrounding Point Reyes National Seashore.
The Greater Farallones National Marine Sanctuary offshore from the park is administered by NOAA. The California coast is one of the most biologically productive regions in the world (Office of National Marine Sanctuaries 2017). Map by NOAA, available at http://farallones.noaa.gov/gallery/maps.html.

plates may converge, which consumes crust and creates mountains; diverge, which allows new crust to form; or slide past each other, which neither creates nor destroys crust. Earthquakes are very common along plate boundaries, which explains the high frequency of earthquakes in California.

Along the California coast, the Pacific plate is moving northwest relative to the North American plate (fig. 4). This type of boundary, where plates slide past each other—lateral displacement—is called a transform boundary. The park is on the Pacific Plate—the largest of Earth's tectonic plates—while the mainland, to the east of Olema Valley, is on the North American plate. Geologists commonly use the analogy that the Pacific plate is moving at about the rate that fingernails grow; estimates range from 3.9–4.2 cm (1.5–1.7 in) per year (Argus and Gordon 2001; Yaemsiri et al. 2010; Field et al. 2015). Over long periods of time, this seemingly small amount of displacement translates to immense amounts of offset. Geologists have long observed the allochthonous—out of place—nature of the Point Reyes terrane. It has almost no similarity to the rocks on the California mainland because it originally formed in a completely different geologic setting in Southern California before being transported north (see "Geologic History" section). Other National Park System units which reflect this tectonic setting are Channel Islands National Park, Pinnacles National Park, and Golden Gate National Recreation Area (see Port 2016).

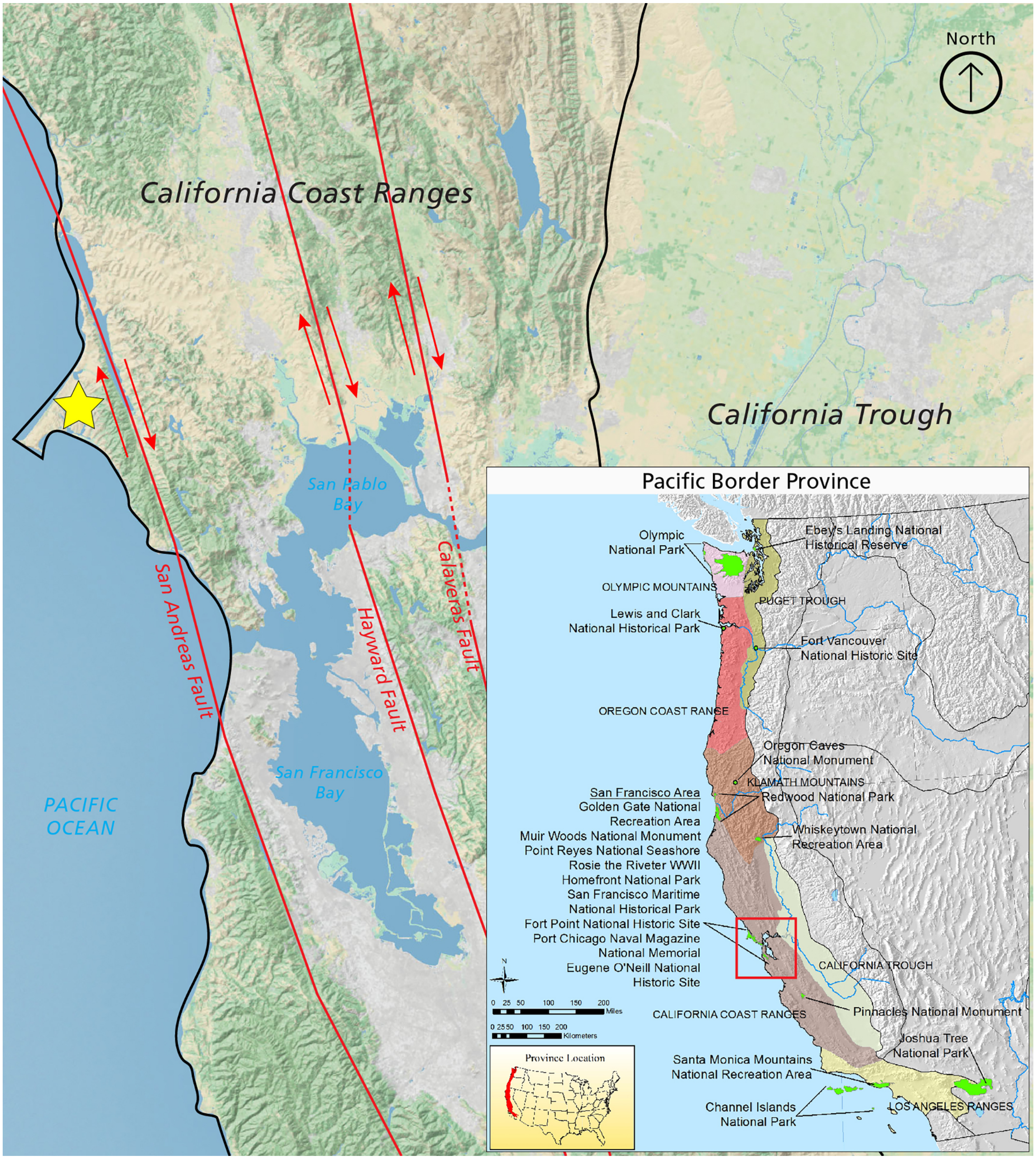


Figure 3. Map of physiographic provinces and sections.
The park is on the western (coastal) edge of the California Coast Ranges section of the Pacific Border Province (inset). The Coast Ranges are a series of parallel mountain ranges separated by valleys which are often occupied by faults. East of the Coast Ranges is the California Trough section which is a large, flat valley that dominates the center of California. The yellow star indicates the location of the park. The red arrows indicate direction of relative fault motion. The red box on the inset graphic indicates the area of detail on the main graphic. NPS graphics: inset map by Jack Wood; main map shaded relief by Tom Patterson with annotations by Rebecca Port.

Table 1. Physiographic features of Point Reyes National Seashore and their associated geology.

*"Rock(s)/Deposit(s)" categories correspond to sections in the "Geologic Features and Processes" section of this report.

Physiographic Feature	Description	Rock(s)/Deposit(s)*	Associated Map Units
Olema Valley	Linear valley—Tomales Bay and Bolinas Lagoon where submerged; surface expression of the San Andreas Fault	*Quaternary sediments*—silt, sand, clay, and gravel of alluvial, estuarine, and eolian origin	QTm, Qml, Qoc, Qtmr, Qoal, Qbmo, Qalo
Inverness Ridge *(includes Tomales Point)*	High and forested, linear ridge parallel to Tomales Bay and Olema Valley	*Cretaceous granitic rocks*—granodiorite and tonalite	MZPZmx, Kgdt, Kgri
Pasturelands	Interior, rolling and grassy hills	*Tertiary marine rocks*—sandstone and shale	Tls, Tm, Tsm, Tps
Sheltered beaches	Beaches and estuaries along Drakes Bay	*Tertiary marine rocks*—sandstone and shale *Quaternary sediments*—terrace, landslide, and beach deposits	Tm, Tsc, Tps, Qmst, Qtmr, Qls, Qbs
Ocean beaches	Ocean-facing, wind-swept beaches	*Quaternary sediments*—beach and dune sand	Qobs, Qdsy, Qbs
Point Reyes Headlands	High, rugged promontory	*Cretaceous granitic rocks*—porphyritic granodiorite *Tertiary marine rocks*—conglomerate	Kg, Tpr

A transform boundary is not a neat separation between tectonic plates. Rather, the boundary is a zone of complex faulting. In recent times the San Andreas has taken up the bulk of the motion between the Pacific and North American tectonic plates. The San Andreas Fault occupies the narrow, linear valley separating the park from the mainland and occupied by Tomales Bay, Olema Valley, and Bolinas Lagoon (fig. 1). 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 3.9–4.2 cm (1.5–1.7 in) per year (Argus and Gordon 2001; Yaemsiri et al. 2010; 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).

A transform boundary did not always exist in California. Prior to about 50 million years ago (fig. 5), the coast was characterized by converging tectonic plates and a subduction zone where an ancient oceanic plate thrust beneath the lighter continental North American plate. The Cretaceous granitic basement rocks underlying the park as well as the Cretaceous and Jurassic Franciscan Complex rocks to the east under Golden Gate NRA formed in association with this ancient tectonic setting. The "Geologic History" section of this report describes the timing of tectonic activity, formation of rocks, and transition from convergent to transform boundary.

Geologic Connections to Other Resources

Just as Point Reyes National Seashore is a geologic outlier, the habitats developed on the geologic foundation are noticeably different from the mainland. Movement along faults shapes watersheds by rearranging drainage, and creating new ponds and shutter ridges (Galloway 1977, see "Fault Topography" section). Vegetation and soils in the park are inherently tied to the geologic foundation. Soil creates a connection between geologic bedrock and modern ecosystems. An NPS Soil Resources Inventory was completed for the park (NPS 2006b) and provides detailed soils information. A number of products associated with the NPS Vegetation Inventory are also available (NPS 2003).

Howell (1949) described 61 plant species from the Point Reyes Peninsula that are not found elsewhere in Marin County. Galloway (1977) ascribed this to the different geologic histories between Point Reyes and the rest of Marin County. For example, Bishop Pines (*Pinus*

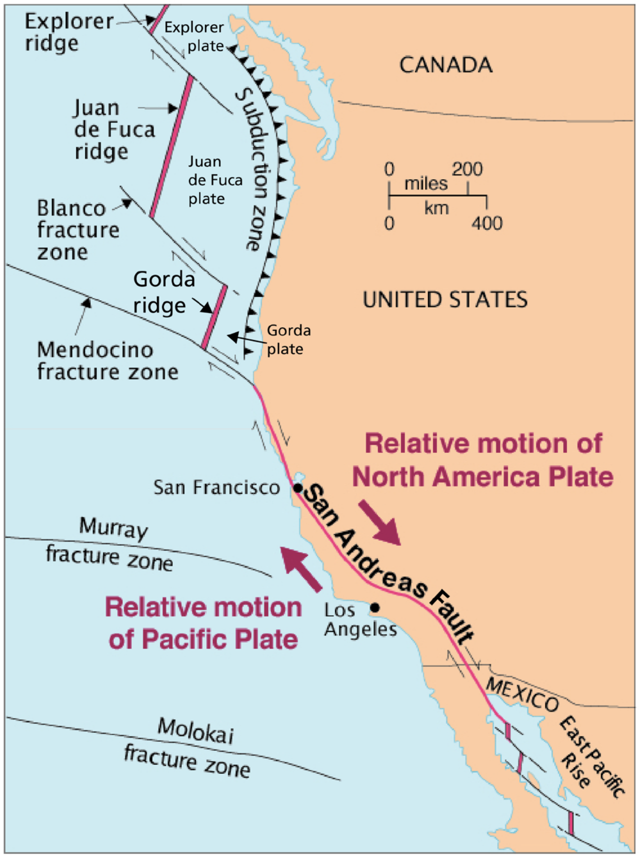


Figure 4. Plate tectonic map of western North America.
The San Andreas Fault alone does not constitute the boundary between the North American and Pacific tectonic plates. This graphic shows all of the features which combined tectonically separate the North American plate from the Pacific plate. The Farallon plate, though mostly consumed by subduction, 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). USGS graphic by Kious and Tilling (1996, figure 25) with additional annotations by Rebecca Port (NPS).

muricata) inhabit areas with shallow, acidic and poorly drained soils associated with the weathering of granitic and shale parent material (Stoffer 2006). Aside from a small grove in the south area of the park, Redwoods are mostly absent; perhaps this is because of the relative dryness of the soil formed on the Monterey Formation (Galloway 1977; Brown et al. 1999).

The Coast Miwok people were the first human inhabitants of the Point Reyes Peninsula. They used sandstone for grinding and preparing food, as well as displaying petroglyphs (Stoffer 2002). The treacherous waters surrounding the park, a result of the rugged geology along the coastline combined with strong winds and currents, caused many shipwrecks, particularly in Drakes Bay. The bay is named after Sir Francis Drake. Historians and archeologists still debate whether Drake wrecked his ship, the *Golden Hind*, there in 1579. The first documented wreck in Drakes Bay occurred in 1595 with the Spanish galleon *San Augustin*. In the 1800s, the Gold Rush brought a wave of immigrant pioneers to the area (Stoffer 2006).

Current land use in the park is a combination of recreation, grazing, and management for preservation of native ecosystems and species. Ancient geologic activity played a part in creating a landscape suitable for grazing. Dairy and beef ranches have grazed and operated on the Point Reyes Peninsula for more than 150 years, and even today, a third of the park is managed as a pastoral zone (7,284 ha [18,000 ac]). Very few other national parks are home to private agriculture, and none to the extent of Point Reyes National Seashore. In some cases, the park has leased the ranches back to the families they originally acquired them from. The Marin Agricultural Land Trust (MALT) is a grassroots organization working to preserve agriculture in West Marin, including Point Reyes. Collaboration between the park and MALT has enabled the preservation of this area from development. Ranching can lead to environmental issues such as overgrazing, habitat degradation, and pollution of streams and estuaries; however, good grazing land management often leads to a more productive mix of plants (Natural Resources Conservation Service 1995). The park has a range management program which works with ranchers to meet environmental rules and regulations (Ben Becker, Point Reyes National Seashore, science advisor, email, 10 September 2017).

Eon	Era	Period	Epoch	MYA		Life Forms	North American Events
Phanerozoic	Cenozoic (CZ)	Quaternary (Q)	Holocene (H)	0.01	Age of Mammals	Extinction of large mammals and birds Modern humans	Ice age glaciations; glacial outburst floods
			Pleistocene (PE)	2.6			Cascade volcanoes (W)
		Tertiary (T) Neogene (N)	Pliocene (PL)	5.3		Spread of grassy ecosystems	Linking of North and South America (Isthmus of Panama)
			Miocene (MI)	23.0			Columbia River Basalt eruptions (NW) Basin and Range extension (W)
		Paleogene (PG)	Oligocene (OL)	33.9			
			Eocene (E)	56.0			Laramide Orogeny ends (W)
			Paleocene (EP)	**66.0**		Early primates	
						Mass extinction	
	Mesozoic (MZ)	Cretaceous (K)		145.0	Age of Reptiles	Placental mammals Early flowering plants	Laramide Orogeny (W) Western Interior Seaway (W) Sevier Orogeny (W)
		Jurassic (J)		201.3		Dinosaurs diverse and abundant	Nevadan Orogeny (W) Elko Orogeny (W)
		Triassic (TR)		**252.2**		Mass extinction First dinosaurs; first mammals Flying reptiles	Breakup of Pangaea begins Sonoma Orogeny (W)
						Mass extinction	
	Paleozoic (PZ)	Permian (P)		298.9	Age of Amphibians		Supercontinent Pangaea intact
		Pennsylvanian (PN)		323.2		Coal-forming swamps Sharks abundant First reptiles	Ouachita Orogeny (S) Alleghany (Appalachian) Orogeny (E) Ancestral Rocky Mountains (W)
		Mississippian (M)		358.9			
		Devonian (D)		419.2	Fishes	Mass extinction First amphibians First forests (evergreens)	Antler Orogeny (W) Acadian Orogeny (E-NE)
		Silurian (S)		443.8		First land plants	
		Ordovician (O)		485.4	Marine Invertebrates	Mass extinction Primitive fish Trilobite maximum Rise of corals	Taconic Orogeny (E-NE)
		Cambrian (C)		**541.0**		Early shelled organisms	Extensive oceans cover most of proto-North America (Laurentia)
Proterozoic		Precambrian (PC, W, X, Y, Z)		2500		Complex multicelled organisms Simple multicelled organisms	Supercontinent rifted apart Formation of early supercontinent Grenville Orogeny (E) First iron deposits Abundant carbonate rocks
Archean				4000		Early bacteria and algae (stromatolites)	Oldest known Earth rocks
Hadean				**4600**		Origin of life Formation of the Earth	Formation of Earth's crust

Figure 5. Geologic time scale.
The divisions of time are organized stratigraphically, with the oldest division at the bottom and the youngest at the top. GRI map abbreviations for each time are in parentheses. The periods in green text are represented by rocks or deposits in the GRI GIS data, Units with less well defined ages are assigned to the Mesozoic and Paleozoic eras (MZPZ units). Compass directions in parentheses indicate the regional locations of events. Boundary ages are millions of years ago (MYA). NPS graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale).

Geologic Features and Processes

These geologic features and processes are significant to the park's landscape and history.

During the 2007 scoping meeting (see KellerLynn 2008), 2016 conference call, analysis of the GRI GIS data, and a literature review, participants (see Appendix A) and the author identified the following geologic features and processes.

- Cretaceous Granitic Rocks
- Tertiary Marine Rocks
- Quaternary Sediments
- Franciscan Complex
- Type Sections
- Folds
- Faults
- Earthquakes
- Landslides
- Lacustrine Features
- Coastal Resources
- Marine Resources
- Paleontological Resources
- Sea Caves
- Geothermal Features and Processes

This section is a summary of information relevant to resource management and/or interpretation at the park and not intended to be a comprehensive review of the geology of Point Reyes National Seashore. Further geologic information is available in the form of park documents, textbooks, guides, journal articles, and webpages; many of these resources are listed in the "Additional Resources" section. A Natural Resources Condition Assessment (NRCA) was in draft by the University of California Berkeley at the time of the 2016 conference call. The park's draft Foundation Document was in review as of July 2016. The Resource Stewardship Strategy (RSS) for the park was never finalized; a draft of it was incorporated into the NRCA (GRI conference call participants, 23 February 2016).

In this report, discussion of geologic features and process (and associated map units) is limited to the Point Reyes National Seashore authorized boundary except where external units, features, and/or processes have the potential to affect park resources. However, the extent of the GRI GIS data far exceeds the park's boundary. The GRI GIS data cover the area of the park, Golden Gate National Recreation Area, Muir Woods National Monument, Fort Point National Historic Site, and much of San Francisco. For geologic information regarding Golden Gate NRA, Muir Woods NM, or Fort Point NHS, refer to the GRI report for those parks (Port 2016).

Maps published by the California Geological Survey (Wagner et al. 2006) and the USGS (Schlocker et al. 1958; Pampeyan 1994; Clark and Brabb 1997; Bonilla 1998; Blake et al. 2000; Brabb et al. 2000) were the sources for the GRI geologic map data that accompany this report. The data is available for download in a Geographic Information System (GIS) format at the GRI publications website: http://go.nps.gov/gripubs. A poster (in pocket) illustrates these data. 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.

Cretaceous Granitic Rocks

Map units within the park boundary: **Kg, Kgri, Kgdt, and MZPZmx**

Cretaceous granitic rocks form the basement (rocks below the sedimentary rocks and deposits) underlying the entire park. The granitic rocks in the park are primarily granodiorite, with lesser amounts of granite and tonalite (table 2), all of which formed during the Late Cretaceous Epoch, between 100.5 million and 66.0 million years ago. In most places they are buried by younger rocks and sediments, however, prominent exposures occur in the park on the Point Reyes Headlands, Inverness Ridge, and Tomales Point (figs. 6 and 7). The geology guide by Stoffer (2006) lists specific locations in the park where Cretaceous granitic rocks may be observed.

Granitic rocks are plutonic and igneous. Igneous rocks are those that formed from the cooling and solidifying of molten material. Plutonic (or "intrusive") rocks occur where molten material cools beneath the surface. Where molten material cools and solidifies at the Earth's surface, volcanic (or "extrusive") igneous rocks form. Volcanic rocks do not occur in the park. The granitic rocks in the park originally formed deep underground as part of a batholith—a massive plutonic body—which was associated with an ancient subduction zone (see "Geologic History" section).

Igneous rocks are further classified by texture (grain size, shape, orientation), as well as the percentage of

Table 2. Cretaceous rocks mapped in Point Reyes National Seashore.

Note: "Location in Park" categories corresponds to physiographic features in table 1. Information in the table was derived from source maps, Stoffer (2006), Clark et al. (1984), and Galloway (1977), except where otherwise noted.

*age refers to original sedimentary rock; metamorphism likely occurred in the Cretaceous Period.

Age of Map Unit from GRI GIS Data	Map Unit (symbol) [color corresponds to GRI GIS data and poster]	Rock Type	Tectonic Setting	Location in Park
Late Cretaceous	Porphyritic granodiorite of Point Reyes (Kg)	*Plutonic igneous rock*—quartz-rich diorite with larger crystals (2–3 cm and up to 5 cm) in a finer-grained crystal matrix.	*Convergent boundary*—originated as part of a batholith in Southern California associated with an ancient subduction zone.	*Point Reyes Headlands*—well exposed, composes Chimney Rock and other sea arches and stacks.
Late Cretaceous	Granodiorite of Inverness Ridge (Kgri)	*Plutonic igneous rock*—quartz-rich diorite and granite. Dikes and masses of aplite and alaskite are common. Contains masses of MZPZmx.	*Convergent boundary*—originated as part of a batholith in Southern California associated with an ancient subduction zone.	*Inverness Ridge*—outcrops are often obscured by vegetation.
Late Cretaceous	Tonalite of Tomales Point (Kgdt)	*Plutonic igneous rock*—hornblende-biotite tonalite that contains dark diorite inclusions. More uniform texture and appearance than Kgri.	*Convergent boundary*—originated as part of a batholith in Southern California associated with an ancient subduction zone.	*Tomales Point* – well exposed in ocean facing cliffs.
Mesozoic and/or Paleozoic*	Metamorphic rocks (MZPZmx)	*Metamorphic rock*—mica schist (foliated), quartzite (non-foliated), and marble (non-foliated).	*Convergent boundary*—originally shale, sandstone, and limestone; altered by contact metamorphism with a batholith in Southern California.	*Inverness Ridge*—occurs as patches and small roof pendants in Kgri.

major minerals (quartz, alkali feldspar, and plagioclase) present in the rock (fig. 8). The granitic rocks in the park are coarse grained. Intrusive rocks tend to be coarser grained than extrusive rocks because they take longer to cool underground and larger crystals are able to grow. Rocks that cool on at the Earth's surface usually exhibit a fine grained (small crystals) texture. The major minerals in the granodiorite, granite, and tonalite are light-colored minerals that are rich in silica. Therefore, the rocks are said to have a felsic composition. In contrast, mafic (containing dark-colored minerals rich in iron and magnesium) rocks of the Franciscan Complex crop out east of the park and the San Andreas Fault (see "Franciscan Complex" section).

Older Metamorphic Rocks

A small area of metamorphic rocks (**MZPZmx**) is included in this section because of its close association with the Cretaceous granitic rocks (see "Geologic History" section). When the still-molten granitic material intruded into the existing layers of rock the heat metamorphosed the overlying limestone, shale, and sandstone into marble, mica schist, and quartzite, respectively (table 2). Metamorphism is the alteration of rocks by any combination of high temperature, pressure, or fluids. It can occur in two primary settings: contact or regional. Contact metamorphism is associated with the intrusion of molten material where rocks adjacent to the intrusion are "baked" by the high temperatures. Regional metamorphism is associated with large-scale tectonic events, such as mountain building events, or "orogenies". The metamorphic rocks in the park likely formed through contact metamorphism with the "roof" of the batholith from which the granitic rocks were derived (Galloway 1977; Stoffer 2006). They are often referred to as "roof pendants" because they likely extended into the batholith from its "roof" but did not melt into it completely.

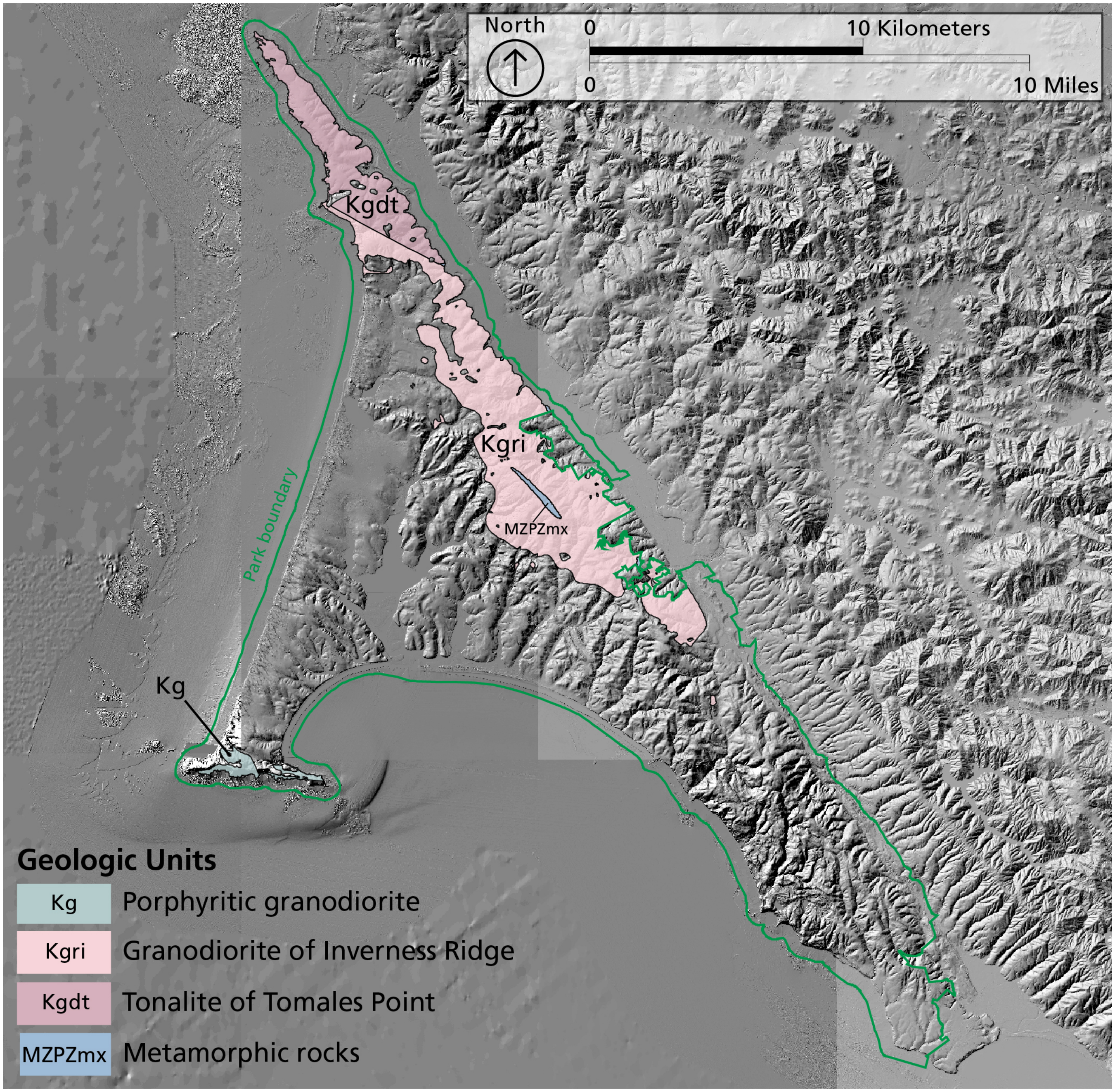


Figure 6. Map of the location of Cretaceous basement rocks in Point Reyes National Seashore. Cretaceous granitic rocks form the basement rock underlying the entire park. Few metamorphic rocks occur within the granite, metamorphosed when the granite was emplaced. In most places basement rocks are covered by sedimentary rocks, however, prominent exposures occur on the Point Reyes Headlands, the north end of Inverness Ridge, and Tomales Point. NPS graphic by Michael Barthelmes using GRI GIS data.

Metamorphism likely occurred during Late Cretaceous time, some 80 million to 100 million years ago. The age of the original, sedimentary rocks is unknown, other than that they must be older than the granite (**Kgri**) which intruded them (Galloway 1977). The "Mesozoic and/or Paleozoic" age reported in the GRI GIS data and on Table 2 refers to the potential age of the original sedimentary rocks. The marble, mica schist, and quartzite in the park probably formed at the same time as the granitic rocks.

Metamorphic rocks are described in terms of their foliation: foliated (minerals are aligned in "stripes") and non-foliated. Marble and quartzite are non-foliated metamorphic rocks. Mica schist is a medium- to high-

Figure 7. Photographs of Cretaceous granitic rocks.
The Tonalite of Tomales Point at McClures Beach (upper photographs) has a more uniform texture and appearance than the granodiorite of Inverness Ridge where dikes and masses of aplite and alaskite (white veins) are common (lower photograph) Upper photographs by Rebecca Port (NPS). Lower photograph copyright © 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org, taken 27 September 2013, used with permission.

grade foliated metamorphic rock. The mica schist in the park is frequently intruded by small, quartz-rich, igneous veins (called aplite dikes).

Erosion has removed most of the metamorphic "roof pendant" rocks in the park. They are mapped along Inverness Ridge between Mount Wittenberg and Mount Vision, but exposures are not common (Stoffer 2006).

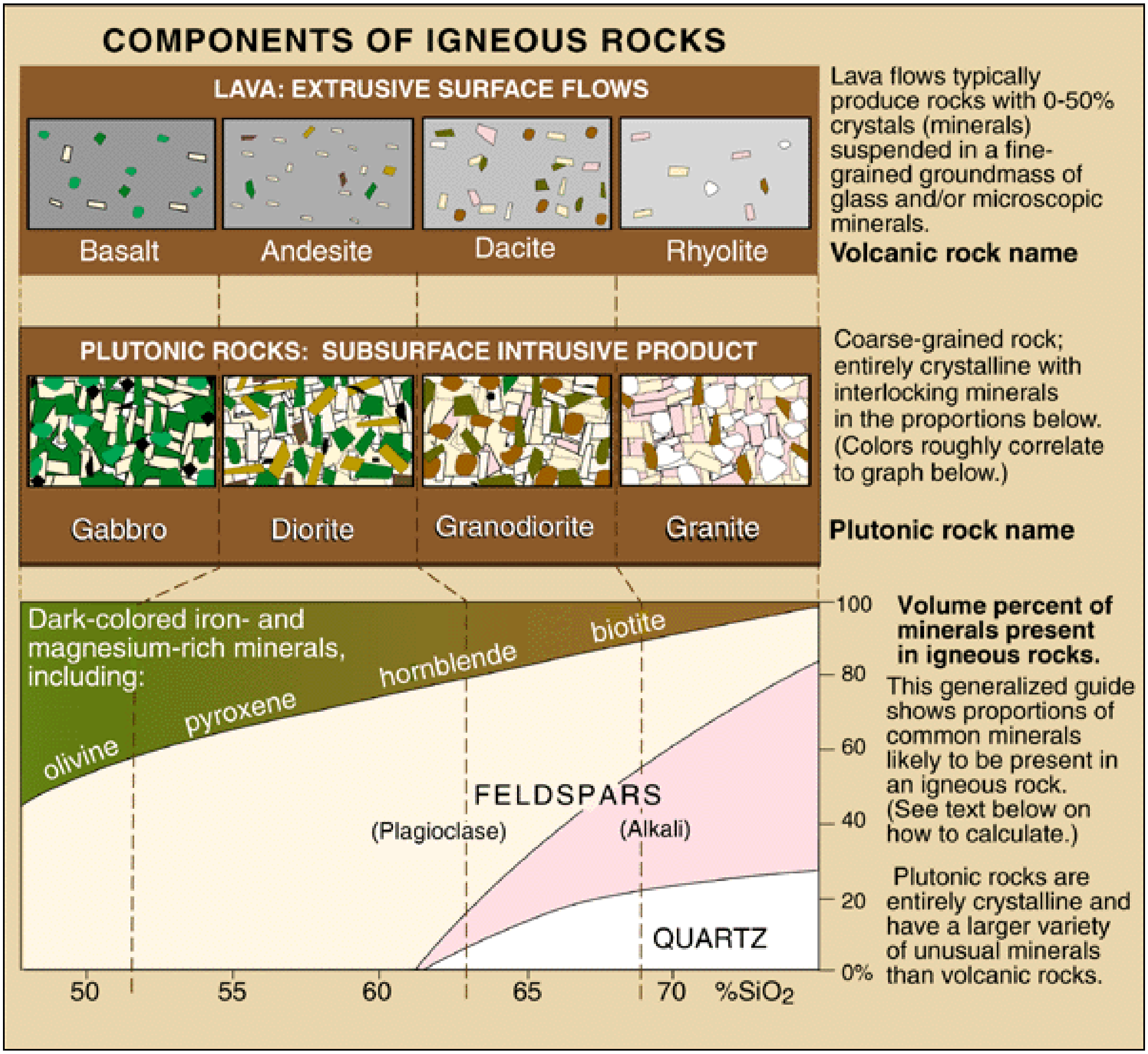


Figure 8. Classification of igneous rocks.
The igneous rocks in Point Reyes National Seashore are primarily granodiorite, with lesser amounts of granite and tonalite. The rocks cooled slowly, deep underground (intrusive) within a massive plutonic body called a batholith, and are therefore coarse-grained. They are of felsic composition (containing primarily light colored minerals). Tonalite is similar to granite except that feldspar is more abundant as plagioclase than as alkali. USGS graphic by J. Johnson, available at https://volcanoes.usgs.gov/vsc/glossary/igneous.html.

Salinian Block

The Cretaceous rocks in the park are at the northern end of an extensive belt of granitic and crystalline metamorphic basement rocks that constitute the Salinian structural block (or Salinian terrane) (fig. 9; Stoffer 2006). A structural block is a region underlain by similar rocks and bounded by faults. Bodega Head is the northernmost land extent of the Salinian block (Galloway 1977, Grove 1993). The Salinian block is bounded to the east by the San Andreas Fault, to the west by the Nacimiento Fault, and to the south by the Big Pine Fault (north of the Transverse Ranges). This now elongated block was a more compact entity prior to Neogene (possibly older) offset along strike-slip faults (Grove 1993). Cretaceous granitic rocks of Point

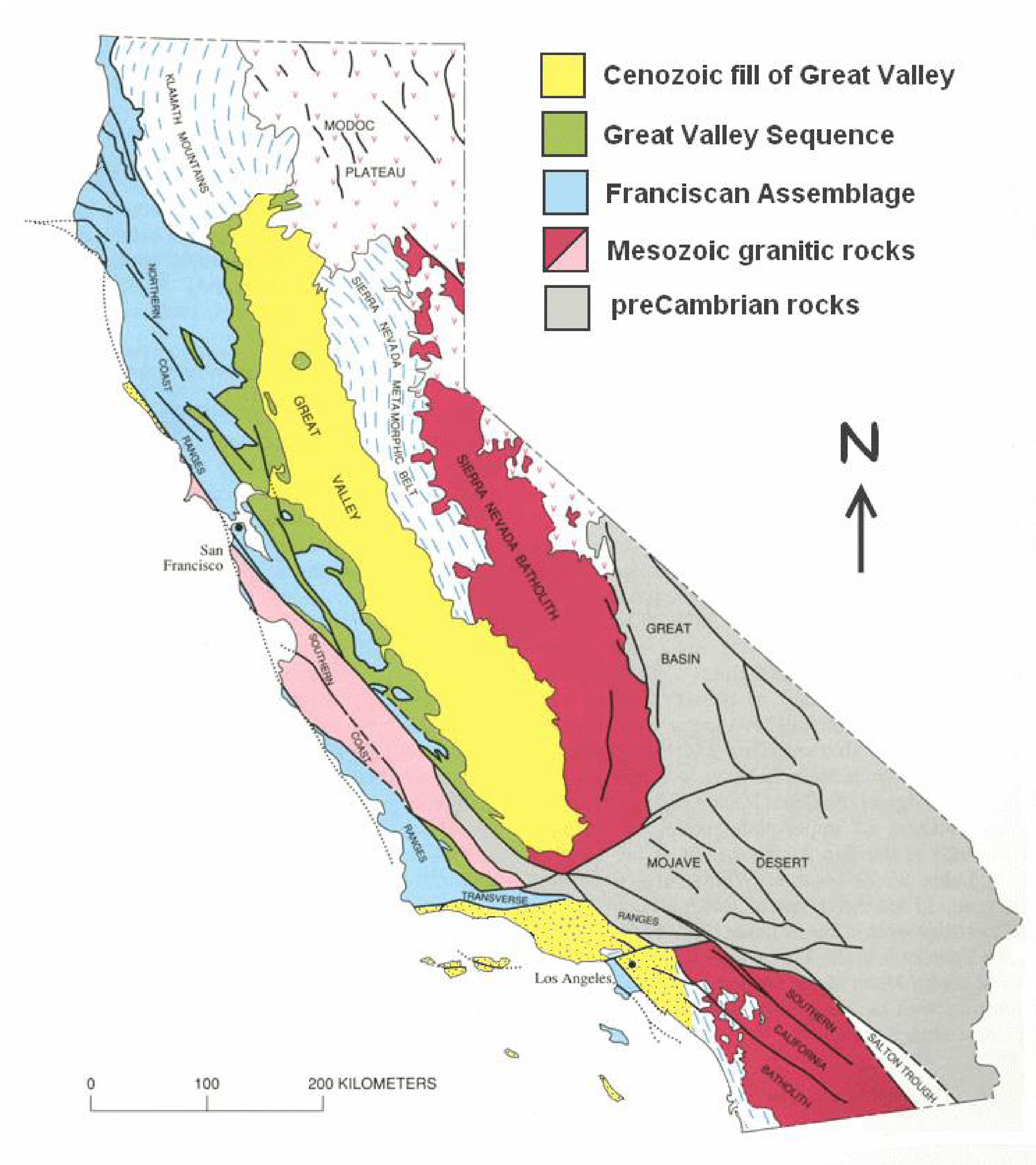


Figure 9. Map of California basement rocks.
The park is underlain by Cretaceous granitic rocks of the Salinian structural block. The Salinian block is shown here in pink. Rocks of the Salinian block originally formed as part of a magmatic arc in geologic settings associated with an ancient subduction zone in southern California. Salinian rocks were displaced by strike-slip faults. Today the rocks are an elongated belt, their northern extent coinciding with the park and Bodega Head. Black lines indicate the locations of major faults. USGS graphic by Irwin (1990, figure 3.3) with additional annotations by Rebecca Port (NPS).

Reyes, Montara Mountain, and the Gabilan Range were all once near the latitude of the Tehachapi Mountains and Mojave Desert, nearly 500 km (300 mi) south of the park's current location (see "Geologic History" section).

Tertiary Marine Rocks

Map units within the park boundary: **Tps**, **Tsc**, **Tsm**, **Tm**, **Tls**, and **Tpr**

Tertiary marine rocks overlie the granitic basement and cover the majority of the geologic map within the park's boundary (fig. 10). The Tertiary Period covers the timespan from 66 million to 2.58 million years ago. Current chronostratigraphic nomenclature has replaced the Tertiary Period with the Paleogene and Neogene Periods (fig. 5). However, in this report, the Tertiary Period will still be referenced as it corresponds to map units of that age ("**T**" map units).

Tertiary rocks in the park are primarily clastic sedimentary rocks deposited in marine or coastal settings. All reflect changes in sea level (see "Geologic History" section). Clastic sedimentary rocks are the products of weathering, erosion, transportation, and deposition of rock fragments called "clasts," and are named after the size of clasts (table 3). Higher-energy depositional environments, such as underwater landslides, deposit larger (heavier) clasts while transporting smaller (lighter) clasts. Where water moves slowly or is stagnant, such as in deep water that is below wave base, the water cannot transport even the smallest clasts and they are deposited. Finer sediments deposited on top of coarser sediments indicate a rise in sea level (transgression), while coarse sediments on top of fine sediments indicate falling sea level (regression) (fig. 11). Examples of rocks in the park deposited in these varying types of conditions are given in table 3.

Table 4 provides a summary of the types and locations of Tertiary marine rocks in the park. The geology guide by Stoffer (2006) provides a thorough yet approachable introduction to sedimentary rocks and their occurrence in the San Francisco Bay region. Galloway (1977), Clark and Brabb (1997), and the Ancillary Map Information Document (goga_geology.pdf, available at http://go.nps.gov/gripubs) provide more comprehensive lithologic descriptions.

Many of the Tertiary units are separated by unconformities. Layers of rock are referred to as "conformable" where they are found to have been deposited essentially without interruption. Although particular sites may exhibit conformable beds representing significant spans of geologic time, no place on Earth contains a full set of conformable strata. Breaks in conformable strata are called "unconformities." Each unconformity represents a period when deposition ceased or where erosion removed previously formed rocks. Because unconformities may be widespread across a region, they can be useful for correlating rock units and tectonic history over long distances.

The Point Reyes Conglomerate—the oldest Tertiary unit in the park and the only from the Paleogene Period—is part of a deposit called a turbidite (fig. 12). During the early Eocene (~50 mya), streams draining the land dumped large quantities of poorly sorted sediments into an ocean basin which had developed on the Salinian block (fig. 13; Grove 1993). 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 at the bottom of the continental slope. This Eocene-age turbidite deposit would eventually lithify and a portion of it is now exposed as the Point Reyes Conglomerate (**Tpr**). In the park, this unit only crops out on the Point Reyes Headlands where it unconformably overlies Cretaceous granitic rocks (fig. 14). Older turbidites (Late Cretaceous age) overlie the granitic basement on the Salinian block south of Monterey (Grove 1993).

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 from 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 fine and coarse layers. The coarse grains of the Point Reyes Conglomerate (**Tpr**) indicate the unit was likely toward the base of a turbidite sequence.

The remaining Tertiary marine rocks (figs. 15–19) consist primarily of finer sediments (sand, silt, and clay) deposited gradually (rather than as a turbidite). Depositional environments range from shallow seas to the deep ocean (table 4).

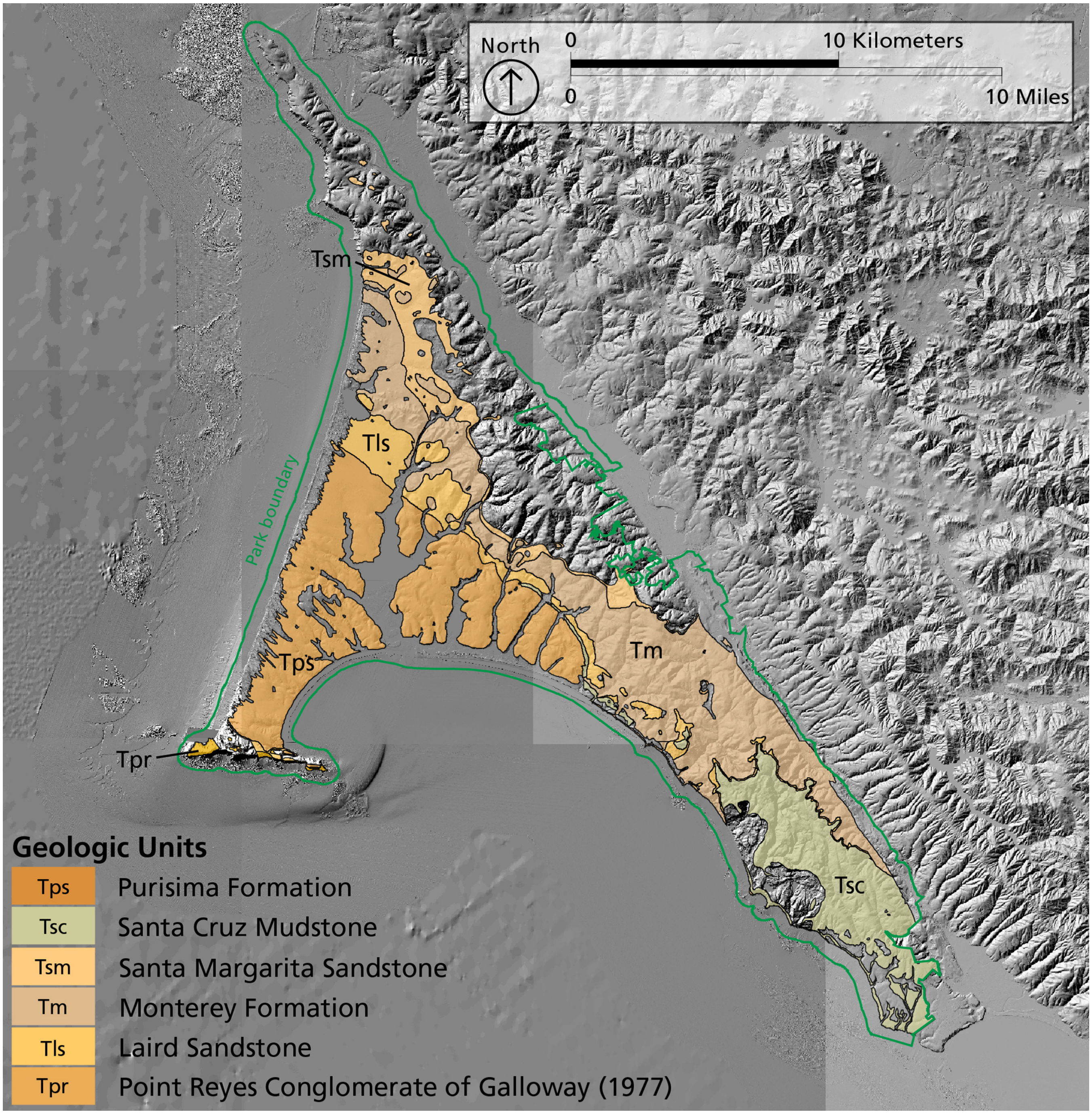


Figure 10. Map of the location of Tertiary marine rocks in Point Reyes National Seashore. Sedimentary rocks, primarily of marine origin, record changes in sea level over the last roughly 56 million years. They overlie the granitic basement rock in the park. NPS graphic by Michael Barthelmes using GRI GIS data.

Table 3. Clastic sedimentary rock classification and characteristics.

*See table 4 for a listing of all sedimentary rock units in the park.
**Claystones and siltstones can also be called "mudstone," or if they break into thin layers, "shale."

Rock Name	Predominant Clast Size	Local Depositional Setting	Examples in the Park* (color corresponds to GRI GIS data and poster)
Conglomerate (rounded clasts) or Breccia (angular clasts)	>2 mm (0.08 in) *[larger]*	Submarine canyon—deposited by a turbidity current (underwater landslide) *[highest energy]*	Point Reyes Conglomerate of Galloway (1977) (Tpr)
Sandstone	1/16–2 mm (0.0025–0.08 in)	Shallow sea—nearshore and beach settings on the continental shelf	Laird Sandstone (Tls)
Siltstone**	1/256–1/16 mm (0.00015–0.0025 in)	Deep ocean—fairly quiet, offshore conditions on the continental shelf	Purisima Formation (Tps)
Claystone**	<1/256 mm (0.00015 in) *[smaller]*	Deeper ocean—below wave base on the continental slope and deeper *[lowest energy]*	Monterey Formation (Tm)

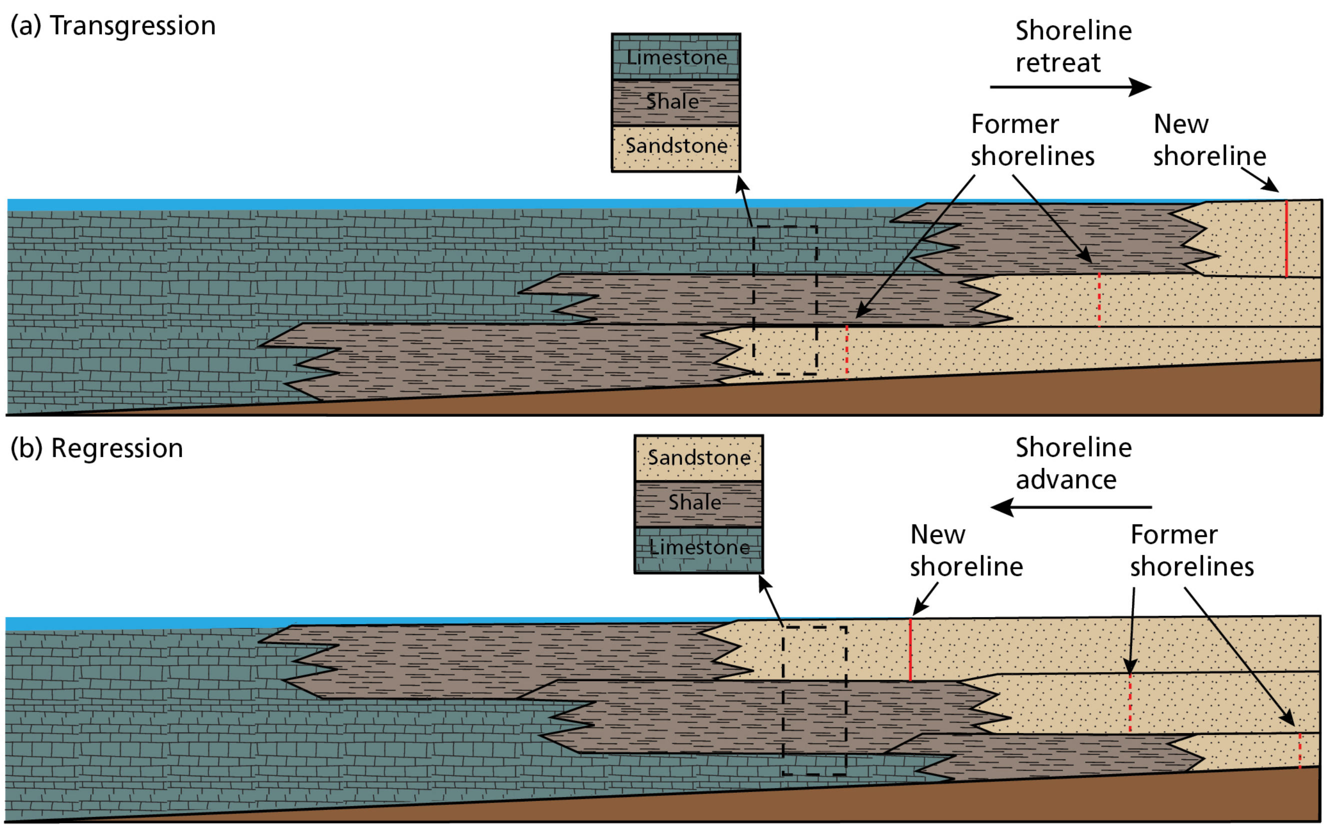


Figure 11. Illustration of a transgressive and regressive rock sequence.
During a transgression (a), the sea advances over the edge of the continent, causing the shoreline to retreat. As the water deepens, land derived sediments (sand) are covered by marine sediments (lime). During a regression (b), the sea retreats and the shoreline advances. Deep-water sediments (lime and mud)are covered by more landward type sediments (sand). Examples of marine transgressions in the park's rock record include the Laird Sandstone (Tls), Monterey Formation (Tm), and Santa Cruz Mudstone (Tsm). Examples of regressive sequences include the Santa Margarita Sandstone (Tsm) and the Purisima Formation (Tps). Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Lillie (2005).

Table 4. Tertiary marine rocks mapped in Point Reyes National Seashore.

Notes: "Location in Park" corresponds to physiographic features in table 1. Information in this table is from source maps (see "Geologic Map Data"), Stoffer (2006), Clark et al. (1984), and Galloway (1977), except where noted.

*numerical ages included where known and cited.

**formerly mapped as Drakes Bay Formation by Galloway (1977).

†Galloway (1977) reported a Paleocene age, however, Kris McDougall (written communication cited in Clark and Brabb 1997) reported an early Eocene age based on fossil foraminifera.

Arkosic—feldspar-rich and usually derived from rapid disintegration of granite.

Bioturbated—reworked or disturbed by organisms (e.g., by burrowing animals or plant roots).

Bituminous—containing much organic or carbonaceous matter.

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

Diatom—a microscopic, single-celled alga that secretes walls of silica, called frustules; lives in freshwater or marine environments.

Foraminifera—protozoans 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.

Glauconite—a greenish silicate (silicon + oxygen) mineral, $(K,Na)(Fe,Al,Mg)_2(Si,Al)_4O_{10}(OH)_2$; may be an indicator of very slow sedimentation.

Porcelanite/Porcelaneous—siliceous rock that is less hard, dense, and vitreous than chert.

Age of Map Unit from GRI GIS Data*	Map Unit (symbol) [color corresponds to GRI GIS data and poster]	Lithologic Description	Depositional Setting	Location in park
Pliocene and Miocene ~7–2.6 MYA (Powell et al. 2007)	Purisima Formation** (**Tps**)	Continuous sequence of marine siltstone with carbonate concretions interbedded with sandstone (fig. 19). Fossiliferous. Deposited on top of the Santa Cruz mudstone, separated by an unconformity.	A shallow sea that was gradually shrinking (records a marine regression). Records a shift from deeper, fairly quiet, off-shore conditions (primarily silts with a lot of diatoms) to shallower near-shore conditions (sandstone deposited from rivers dumping into estuaries and bays). This unit has been offset from its source at a rate of 5 cm/year for the last 7 million years (Atwater and Stock 1998).	*Pasturelands*—around Drakes Estero; good exposures in cliffs around Drakes Bay (fig. 19); exposures along the Coast Trail as canyon cuts downhill toward beach through increasingly younger beds of the Purisima Formation.
late Miocene	Santa Cruz Mudstone** (**Tsc**)	Sandy and glauconitic base grades upward into siliceous mudstone with carbonate concretions (fig. 18). About 2,000 m (6,600 ft) thick at the southern end of the peninsula at Bolinas but pinches out to the east of Drake Bay. Complexly folded and faulted, but mostly dips westward 20–60°. Conformably overlies the Santa Margarita Sandstone	On the continental shelf or slope, in ocean depths of 140–180m (450–600 ft); sandy base was deposited in shallower conditions than the overlying mudstone (records a marine transgression). Similar conditions to those about a kilometer (half a mile) off the coast today. The silts and clays came from nearby rivers. Silica came from the remains of diatoms. After burial, the silica from the diatoms dissolved and later re-precipitated as cement that bound the silt and clay particles together.	*Inverness Ridge*—southeastern portion of the peninsula; exposed in the sea cliffs at Palomarin Beach and southward to the end of the peninsula at Duxbury Point. Largely responsible for many of the topographic characteristics of the area; landslide deposits (Qls) at Double Point are mainly masses of Tsc.

Age of Map Unit from GRI GIS Data*	Map Unit (symbol) [color corresponds to GRI GIS data and poster]	Lithologic Description	Depositional Setting	Location in park
late Miocene 7.9 ± 0.3 MYA (Clark and Brabb 1997)	Santa Margarita Sandstone** (**Tsm**)	Massive, arkosic sandstone; green where glauconitic; bituminous and bioturbated in cliffs near Double Point (fig. 17). East of Drakes Bay, unconformably overlies the Monterey Formation.	Shallow sea; glauconite may indicate deposition in shallow water with very little sedimentation. Represents a marine regression from the deposition of the underlying Monterey Formation; regressive sequence is not fully recorded because formations are unconformable.	*Pasturelands*—Primarily mapped along a faint northwest-trending escarpment in the vicinity of the Environmental Education Center. A few very small areas mapped on the Point Reyes Headlands and in sea cliffs near Double Point.
late and middle Miocene 15.5–7.5 MYA (Clark et al. 1984)	Monterey Formation (**Tm**)	Porcelaneous shale with chert, mudstone, diatomite, and calcareous claystone (fig. 16). Some interbeds of arkosic sandstone. Total thickness is on the order of 1,500 m (5,000 ft) although the entire section is not visible at any one location. Conformably overlies Laird Sandstone which grades upward into finer-grained rocks (sandstone, siltstone and shale) of the lower Monterey Formation.	Deep ocean, as indicated by benthic foraminifera. Lower part of formation was deposited in shallower water; formation records a marine transgression. Chert is contorted in some outcrops, suggesting the mass of beds slid down the continental shelf while pliable (Curay 1965). Probably entirely covered Inverness Ridge at one point but later eroded from the northern part. The Monterey Formation is the source rock for the majority of the oil in California.	*Pasturelands/ Inverness Ridge*—mapped as a thick band along the west side of Inverness Ridge extending onto the pasturelands. Good cliff exposures of dipping strata at Kehoe Beach. Poorly exposed in the upland region east of the Environmental Education Center
middle Miocene	Laird Sandstone (**Tls**)	Arkosic sandstone, friable, and contains calcareous concretions. Granitic boulder conglomerate with abundant barnacle fragments at the base. Fossiliferous units are more well-cemented and resistant to erosion. Thick-bedded to massive. As much as 64 m (210 ft) exposed at Kehoe Beach (fig. 15); thins to the east. Unconformably overlies Cretaceous granitic basement where Tpr is absent.	Shallow sea (nearshore) and beach setting that marks the return of the sea onto the Point Reyes Peninsula. Clasts derived from weathering of Salinian basement rocks. Sediments record a quiet transgressive sea, advancing gently across an old irregular eroded granitic surface. Grades conformably by interstratification upward into the (deeper water) Monterey Formation. Probably entirely covered Inverness Ridge at one point but later eroded from the northern part.	*Pasturelands/ Inverness Ridge*—mapped as a thin, discontinuous band along the west side of Inverness Ridge extending onto the pasturelands. Good cliff exposures of dipping strata north of Kehoe Beach. Poorly exposed in the upland region east of the Environmental Education Center.

Age of Map Unit from GRI GIS Data*	Map Unit (symbol) [color corresponds to GRI GIS data and poster]	Lithologic Description	Depositional Setting	Location in park
early Eocene†	Point Reyes Conglomerate of Galloway (1977) (**Tpr**)	Arkosic sandstone and conglomerate. Beds dip steeply (35–45° NW). As much as 210 m (690 ft) crops out on Point Reyes Headlands. Unconformably overlies Salinian basement rocks.	Deposited in the upper mid-fan area of a submarine channel by a turbidity current (underwater landslide) (fig. 12). Originated in southern California and transported to modern location by fault movements (fig. 13). Clasts were derived from weathering of underlying granitic rocks, as well as a silicic volcanic or older conglomerate terrane to the east and southeast which no longer exists (eroded away).	***Point Reyes Headlands***—only mapped on the Point Reyes Headlands. The lighthouse is built on this unit; it also caps Chimney Rock.

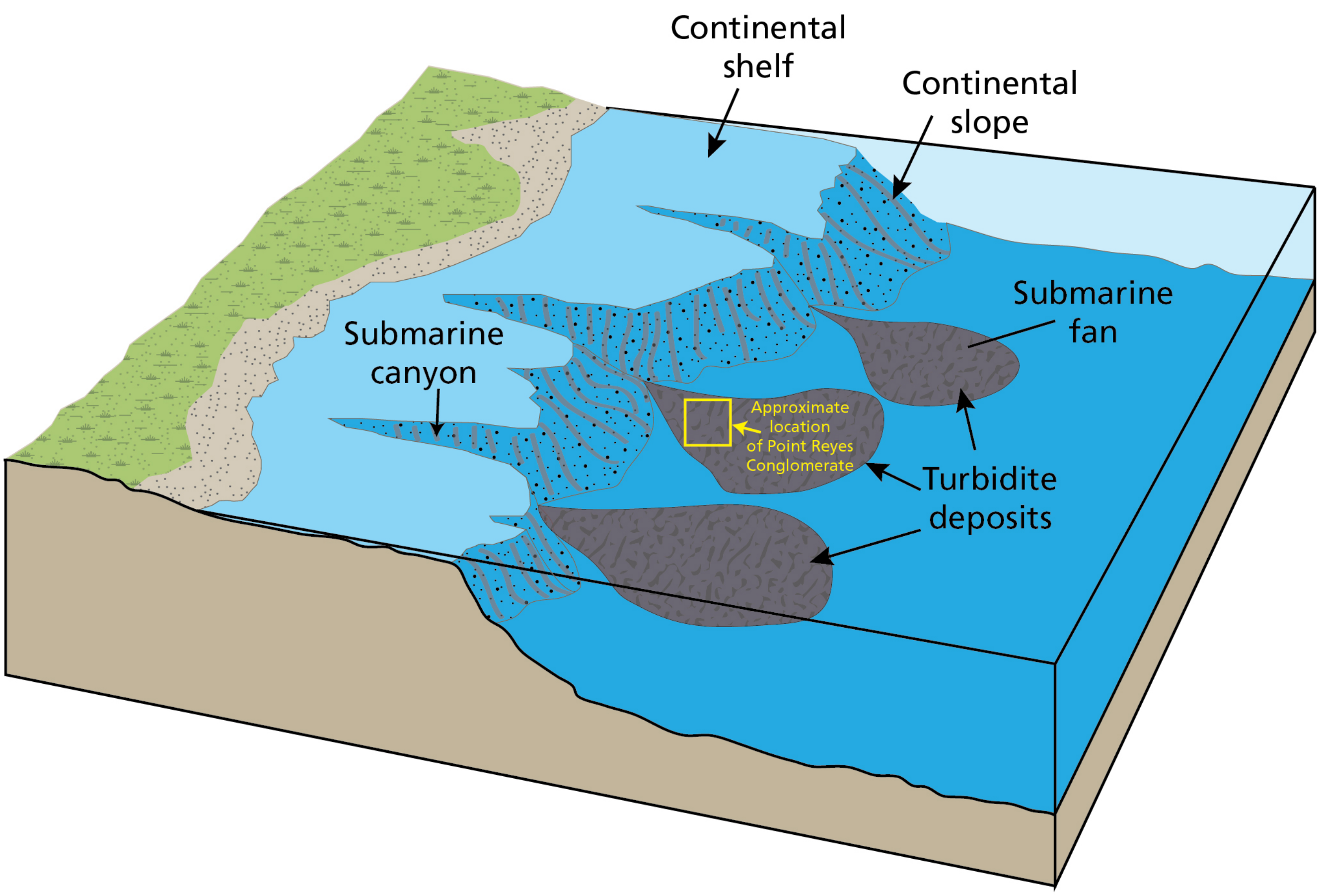


Figure 12. Illustration of turbidite depositional environment.
Turbidites form when a mass of sediments that has accumulated on the continental shelf tumbles down the steep continental slope and into deep water in a density-driven underwater landslide. Turbidites typically display an upward fining sequence known as graded bedding. The Point Reyes Conglomerate of Galloway (1977) (Tpr) is a deposit from the upper mid-fan area of a turbidite. NPS graphic by Rebecca Port after Tarbuck et al. (2011).

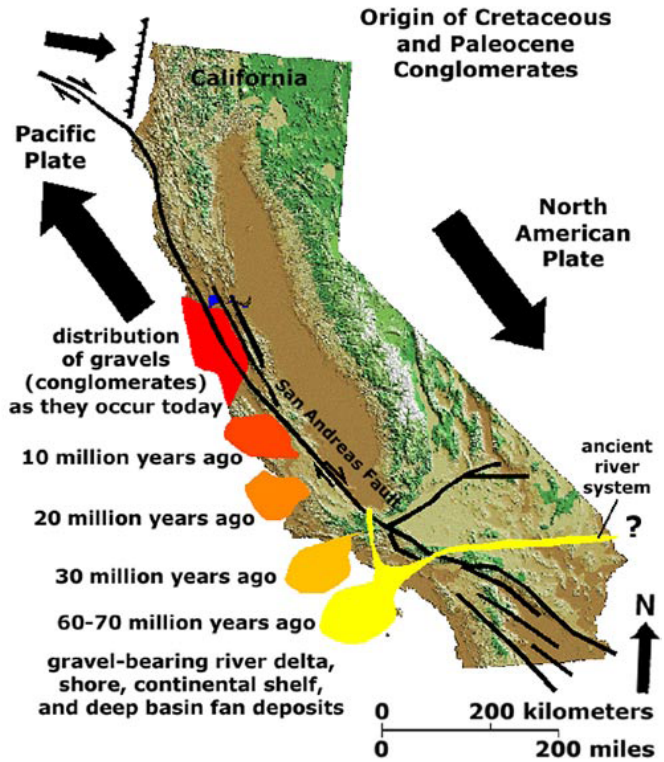


Figure 13. Map displaying inferred origin of Point Reyes Conglomerate.
Cretaceous and Tertiary conglomerates in the San Francisco Bay region originated in Southern California. Movement along the San Andreas and older faults transported the rocks northward. The Point Reyes Conglomerate of Galloway (1977) (Tpr) was deposited approximately 50 million years ago. USGS graphic in Stoffer (2002, p. 33).

Figure 14. Photographs of the Point Reyes Conglomerate.
This conglomerate and sandstone unit is only mapped on the Point Reyes Headlands. As much as 210 m (690 ft) crops out (Clark and Brabb 1997) near the Point Reyes lighthouse (left photograph) where it unconformably overlies the granitic basement (not shown). The clasts (right photograph) were derived from weathering of Cretaceous granitic rocks as well as a now absent volcanic terrane or older conglomerate. The clasts accumulated on the continental shelf until they were entrained in a turbidity current (underwater landslide) and brought to rest in the upper area of a submarine fan extending from a submarine canyon. USGS photographs by Phil Stoffer, available at https://3dparks.wr.usgs.gov/pore/html2/thumbs.htm.

Figure 15. Photograph of geologic features north of Kehoe Beach.
The Laird Sandstone is exposed in cliffs north of Kehoe Beach where it unconformably overlies Cretaceous granitic rocks; the Point Reyes Conglomerate is absent. The GRI GIS data reports two faults and two folds (a syncline and an anticline) in this area (see poster, in pocket). The approximate location of a high-angle fault (arrows show direction of displacement) and syncline are visible on the photograph. The massive beds of Laird Sandstone (Tls) are offset by the fault by about 40 m (130 ft). Photograph copyright © 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org, taken 27 September 2013, used with permission.

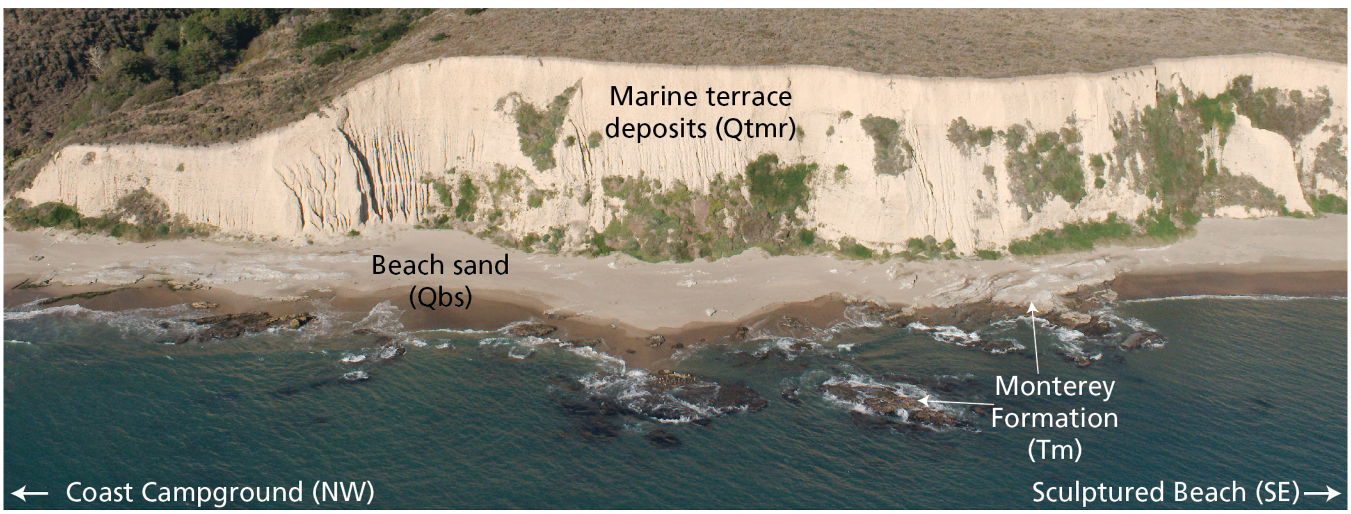


Figure 16. Photographs of the Monterey Formation.
Exposures of dipping beds of the Monterey Formation occur from Sculptured Beach northwest to near Coast Campground. The Monterey Formation is silica-rich and fine-grained, primarily shale, mudstone, and chert, indicating deposition in deep water. Chert is contorted in some outcrops, suggesting the mass of beds slid down the continental shelf while pliable (Curay 1965). The cliffs behind the beach are part of a marine terrace—an uplifted wave-cut platform (bottom photograph). The terrace is covered in unconsolidated silt, sand, and gravel. Beach sand overlies the active wave-cut platform. The Purisima Formation and Santa Cruz Mudstone are not present in this location. Top photographs by Rebecca Port (NPS). Bottom photograph copyright © 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org, taken 27 September 2013, used with permission.

Figure 17. Photograph of the Santa Margarita Sandstone.
Below the Elephant Seal Overlook at the end of Chimney Rock Road on the Point Reyes Headlands, the Santa Margarita Sandstone (Tsm) crops out beneath the Purisima Formation (Tps) in coastal cliffs. Both formations are fossiliferous. Photograph by Lillian K. Pearson (NPS).

Figure 18. Photograph of a Santa Cruz Mudstone slump block.
An angular unconformity separates the older, steeply-dipping Santa Cruz Mudstone (Tsc) from younger Quaternary marine and stream terrace deposits (Qmst). The photograph shows a block of these units which has slumped toward shore and rotated the marine and stream deposits so that they are dipping inland; many slump blocks of Santa Cruz Mudstone occur in the Palomarin area. A stream is falling along the escarpment of this large slump block (Stoffer 2006). USGS photograph by Phil Stoffer, available at https://3dparks.wr.usgs.gov/pore/html2/pore_081.htm.

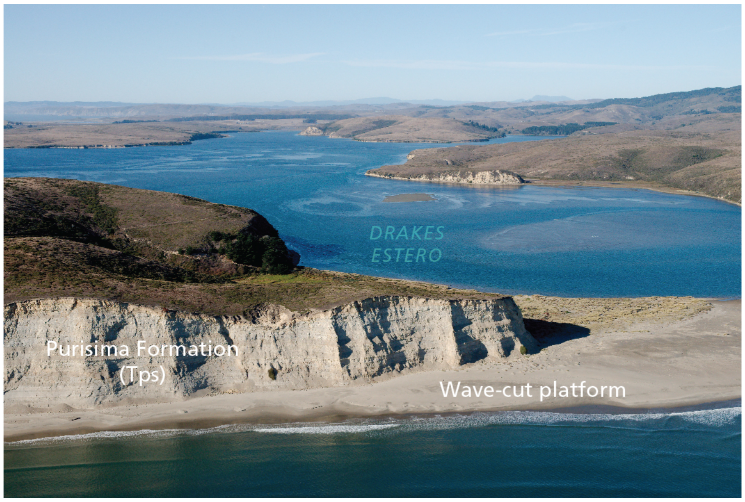


Figure 19. Photographs of the Purisima Formation.
Siltstone of the Purisima Formation is exposed in sea cliffs which tower more than 30 m (100 ft) above Drakes Beach. Drakes Beach is an active wave-cut platform covered in beach sediments (right photograph). At low tide more of the platform is exposed and at high tide the ocean may come up to the base of the cliffs. Left photograph by Lillian K. Pearson (NPS). Right photograph copyright © 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org, taken 27 September 2013, used with permission.

Quaternary Sediments

Map units within the park boundary: **Qbs**, **Qdsy**, **Qalo**, **Qbmo**, **Qls**, **Qobs**, **Qoal**, **Qtmr**, **Qmst**, **Qoc**, and **QTm**.

The youngest map units in the GRI GIS data were deposited during the Pleistocene and Holocene epochs, which together are termed the Quaternary Period and include the past 2.58 million years. The GRI GIS data show a variety of Quaternary sediments in the park (fig. 20, table 5) and include bay mud, beach sand, marine and stream terrace deposits, alluvium, dune sand, and landslide deposits.

Each of these Quaternary ("**Q**") units is associated with processes that are still active in the park today. Most were deposited by running water, wind, and/or slope movements (table 5). Fluvial is the term used to describe processes related to running water, and the resulting deposit is called alluvium. Deposition of alluvium in the park occurrs in stream beds and valleys, stream terraces, marine terraces, and on deltas and floodplains. Eolian refers to erosion and deposition by wind. Eolian deposits in the park occur along the coast and include beach and dune sand (fig. 21). Slope movements refer to the transfer of material due to gravity (see "Landslides" section). Deposits from slope movements vary widely in size and may occur wherever there are steep slopes; only slope movement deposits large enough to map at 1:48,000-scale are shown on the map (see poster, in pocket).

Formally named "**Q**" units are the oldest Quaternary units mapped in the park and all formed in depositional settings associated with the San Andreas Fault. These units include the Merced Formation (**QTm**) and the Olema Creek Formation (**Qoc**). The Millerton Formation (**Qml**) is mapped on the east side of Tomales Bay, outside of the park but within Golden Gate NRA. Due to its proximity to the park and association with the Olema Creek Formation, it is included in Table 5. The Millerton and Olema Creek formations are contemporaneous (formed at the same time) alluvial and estuarine sediments deposited in the valley formed by the San Andreas Fault. The older Merced Formation accumulated in a slowly subsiding basin adjacent to the fault.

The nature and distribution of Quaternary sediments provide clues to the recent history of natural processes in the park. Alluvium deposited on old stream terraces are found at isolated high points on Inverness Ridge indicating former drainage patterns, long before the ridge was worn down to its current state (Galloway 1977). The alluvium (**Qalo**) in the lower reaches of the stream valleys leading into Drakes Estero and Estero de Limantour show the extent to which these estuaries were drowned during a period of high sea level, probably following the last glacial stage (see "Geologic History" section; Galloway 1977). Modern alluvium is accumulating today where streams reach the estuaries and drop much of their sediment load. The large marine terrace north of Bolinas is covered in layers of Quaternary sediments. Marine terraces are uplifted wave-cut platforms, and are evidence of ancient coastlines (see "Coastal Resources" section). Elevated marine terraces along with ancient alluvial and coastal dune deposits (fig. 21) suggest that the Point Reyes Peninsula has been rising throughout the Quaternary Period (see "Point Reyes Fault" section).

Franciscan Complex

Map units within the park boundary: **Kfl**, **KJfss**, **KJfm**

In the area of the park, Franciscan Complex rocks occur east of the San Andreas Fault and as such are only mapped in the park in a few very small areas within Olema Valley. Franciscan rocks do occur throughout the north district of Golden Gate NRA (see Port 2016). Rocks of the Franciscan Complex include basalt, greenstone, chert, limestone, graywacke (sandstone), shale, and serpentinite. Franciscan rocks are mapped as mélange where they are so thoroughly ground together that they cannot be distinguished as individual rock units. This mélange separates more coherent blocks of Franciscan rocks called terranes. Only limestone and chert (**Kfl**), graywacke and shale (**KJfss**), and mélange (**KJfm**) are mapped in the park (Table 6).

The Franciscan Complex is an accretionary wedge—an accumulation of sediment and rock that collected in a deep oceanic trench—that amassed from about 160 million to 50 million years ago (Elder 2013). 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 terrestrial sediments eroded and transported into the ocean and from oceanic crustal rocks scraped off of the subducting Farallon 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 were metamorphosed (altered by heat, pressure, and/or hydrothermal fluids) in the subduction zone and accreted (attached) to the overriding (non-subducting) North American continental plate.

While graywacke and shale (**KJfss**), and mélange (**KJfm**) are common in the Francisan Complex east of the park, map unit Kfl is unique because it is only mapped in Olema Valley, just south of Five Brooks. **Kfl** is limestone of the Calera Formation. The presence of Calera Limestone reveals an important clue about the geologic development of the San Andreas Fault zone

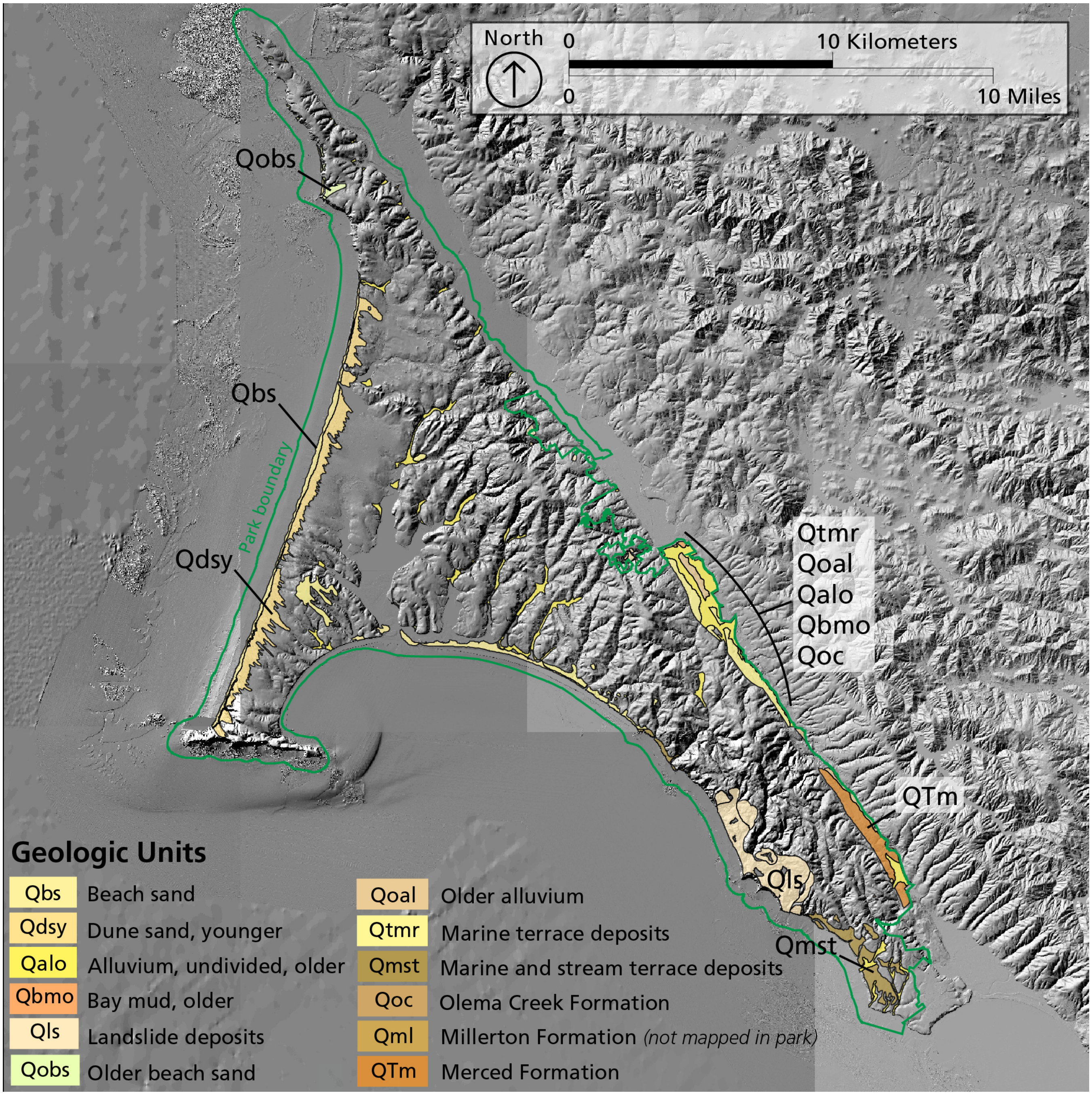


Figure 20. Map of the location of Quaternary sediments in Point Reyes National Seashore. Quaternary sediments are the youngest units mapped in the park. They were deposited by processes that are still active in the park today such as waves, flowing water, wind, and/or slope movements. NPS graphic by Michael Barthelmes using GRI GIS data.

Table 5. Quaternary deposits in Point Reyes National Seashore.

Notes: "Location in Park" corresponds to physiographic features in table 1. Information in this table was derived from source maps (see "Geologic Map Data" section), Stoffer (2006), Clark et al. (1984), and Galloway (1977), except where otherwise noted.

Age of Map Unit from GRI GIS Data	Map Unit (symbol) [color corresponds to GRI GIS data and poster]	Description	Depositional Setting	Location in Park
Quaternary	Beach sand (Qbs)	Well to moderately sorted sand with some fine gravel.	Modern beaches.	*Ocean beaches*—lines the northwest coast of the peninsula (Point Reyes Beach, Kehoe Beach and McClures Beach) and the southern coast along Limantour Spit.
Quaternary	Dune sand, younger (Qdsy)	Sand; overlapping tongues and narrow parabolas pointing southeast (Cooper 1967).	Deposited by wind (eolian processes).	*Ocean beaches*—along the northwest coast of the peninsula (Point Reyes Beach, Kehoe Beach and McClures Beach), inland from beach sand.
Quaternary	Alluvium, undivided, older (Qalo)	Clay, silt, sand, and gravel.	Deposited by rivers and streams.	*Inverness Ridge*—fills valleys along ridge leading to bays, esteros, and the ocean.
Quaternary	Bay mud, older (Qbmo)	Water-saturated clay, silt, and sand.	Deposited by rivers and streams on a coastal plain.	*Olema Valley*—at the head of Tomales bay, near the mouth of Lagunitas Creek.
Quaternary	Landslide deposits (Qls)	In the south, deposits consist of intact to highly disrupted masses of Santa Cruz Mudstone. In the north, deposits consist of debris from the Granodiorite of Inverness Ridge.	Deposited by landslides; debris flows and block slumps.	*Sheltered beaches*—mapped along Wildcat Beach, Double Point, and Abalone Point; amid Crystal, Pelican, and Bass lakes; over parts of the Coast Trail and Ocean Lake Loop. *Inverness Ridge*—mapped along northeast side of ridge, near the head of Tomales Bay. Note: only landslide deposits large enough to be discernible at 1:48,000-scale were mapped. Many small debris flows, slumps, and rockfalls occur throughout the park, especially along coastal cliffs.
late Pleistocene?	Older beach sand (Qobs)	Reddish brown, friable sand with some fine gravel. Noticeably more red/orange than the gray/tan sand on the active beach (fig. 21).	Ancient dune sands, probably accumulated in a coastal valley which existed before or during the last ice age. Nonconformably overlies Tonalite of Tomales Point (fig. 21).	*Ocean beaches*—along northwest coast of peninsula.

Age of Map Unit from GRI GIS Data	Map Unit (symbol) [color corresponds to GRI GIS data and poster]	Description	Depositional Setting	Location in Park
Quaternary	Older alluvium (Qoal)	Poorly indurated siltstone, sandstone, and conglomerate. Cross bedding is common. Contains small wood fragments in some places.	Originally deposited in alluvial fans and stream channels; today appears as gently rolling hills, little or no ancient alluvial surfaces preserved.	***Olema Valley***—around Olema and Point Reyes Station.
Quaternary	Marine terrace deposits (Qtmr)	Unconsolidated sand, silt, and gravel.	Combination of marine, eolian, and alluvial origins; deposited on uplifted wave-cut terraces.	***Olema Valley***—around Olema and head of Tomales Bay. ***Sheltered beaches***—near Coast Campground (fig. 16) and surrounding Drakes Estero.
Quaternary	Marine and stream terrace deposits (Qmst)	Weakly consolidated sand, silt, and gravel.	Marine and alluvial origins; deposited on uplifted stream- and wave-cut terraces.	***Sheltered beaches***—along coast, north of Bolinas.
late Pleistocene	Olema Creek Formation (Qoc)	Thinly bedded, laminated clayey siltstone interbedded with coarse gravel, organic material is abundant. Contains freshwater diatoms and wood. Overlain by alluvium and stream terrace material.	Alluvial and estuarine origins; deposited on a coastal plain near a bay head in the valley formed by the San Andreas Fault. Contemporaneous with the Millerton Formation.	***Olema Valley***—along the San Andreas Fault near Olema.
late Pleistocene	Millerton Formation (Qml)	Clay, silt, sand, and gravel.	Alluvial and estuarine origins; deposited in an inlet (similar to present day Tomales Bay) which filled a portion of the valley created by the San Andreas Fault. Contemporaneous with the Olema Creek Formation.	***Olema Valley***—east side of Tomales bay and east of the San Andreas Fault. Not mapped in park, but is in the north district of Golden Gate NRA.
Quaternary and late Pliocene	Merced Formation (QTm)	Siltstone containing foraminifera alternating with fine-grained, crossbedded sandstone containing shell fragments and carbonized wood within calcareous concretions.	Deposited in a small, slowly subsiding sedimentary basin that developed along the San Andreas Fault. Fossiliferous marine beds alternate with terrestrial beach, dune, and shore deposits. Where buried, farther inland, it is a significant groundwater aquifer for San Francisco and San Mateo counties.	***Olema Valley***—east of San Andreas Fault and south of Tomales Bay. Outside of park, forms the cliffs at Bolinas and Fort Funston..

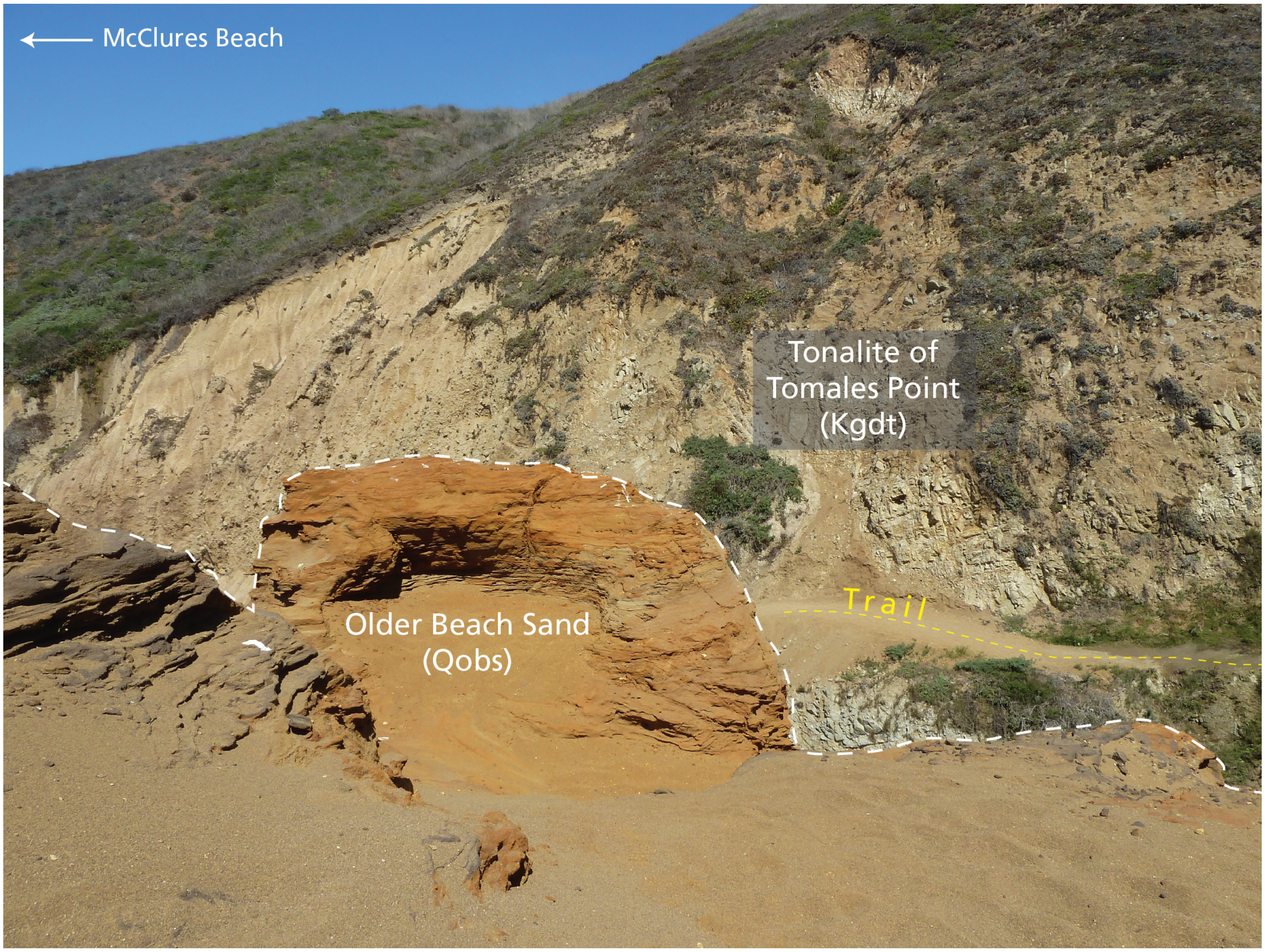


Figure 21. Photograph of geologic features at McClures Beach.
Ancient dune sands (foreground) nonconformably overlie the Tonalite of Tomales Point (background) at McClures Beach. Eolian processes (wind) probably deposited the dunes in a coastal valley which existed during the last ice age. A modern valley (occupied by a trail) is now eroding into the ancient dunes and exposing the contact with the underlying tonalite (Stoffer 2006). View is to the north. NPS photograph by Rebecca Port.

Table 6. Franciscan Complex map units in Point Reyes National Seashore.

Notes: "Location in Park" corresponds to physiographic features in table 1. Information in this table is from source maps (see "Geologic Map Data" section), Stoffer (2006), and Clark et al. (1984).

Age of Map Unit from GRI GIS Data	Map Unit (symbol) [color corresponds to GRI GIS data and poster]	Rock or Sediment Type	Tectonic and Depositional Setting	Location in Park
Cretaceous	Franciscan Complex, limestone and chert (Kfl)	Interbedded limestone and chert	*Deep ocean*—accumulated as limey sediments on the crest of a submarine volcano or plateau. Formed near the equator and transported to current location along pre-San Andreas faults.	*Olema Valley*—only mapped in one location along between Olema and Bolinas. Straddles the boundary between the park and Golden Gate NRA. Not mapped anywhere else in GRI GIS data.
Cretaceous and Jurassic	Franciscan Complex, sandstone and shale (KJfss)	Interbedded graywacke sandstone and fissile shale. Bed thickness varies. Severely sheared in some areas. Lacks tectonic inclusions of other Franciscan rock types. Forms resistant topography (Bolinas Ridge).	*Subduction zone*—turbidites deposited in the oceanic trench of the Franciscan subduction zone by underwater landslides.	*Olema Valley*—a few small areas along the park boundary south of the Bear Valley Visitor Center; part of a much larger area mapped on Bolinas Ridge.
Cretaceous and Jurassic	Franciscan Complex, mélange (KJfm)	A mixture of Franciscan rocks too small to be mapped separately including greenstone, chert, graywacke sandstone, and shale, and their metamorphic equivalents. Often highly sheared.	*Subduction zone*—formed as Franciscan rocks were ground together and sheared during accretion to the North American continent.	*Olema Valley*—small area mapped on the park boundary near the Bear Valley Visitor Center; part of a much larger area east of the park.

in Olema Valley. The mid Cretaceous-age limestone does not correlate with the older Franciscan graywacke, basalt, and greenstone on the east side of the fault zone on Bolinas Ridge, nor does it correlate with the Salinian basement and Tertiary marine rocks of Inverness Ridge to the west (Stoffer 2006). The outcrop near Five Brooks appears to be a tectonic inclusion—a thin sliver of limestone bounded by faults—within the fault zone (Galloway 1977). In the 1850s, efforts were made to quarry some of the limestone deposits in this area (see "Documentation and Reclamation of Abandoned Mineral Lands" section).

Type Sections

The place where a rock formation is best exposed is referred to as a "type locality." More particularly, an outcrop may display the formation so well as to become a reference location referred to as "type section." Type localities and type sections have both scientific and educational significance and are commonly "stops" on geological field trips. Because type localities and type sections typically occur where a formation was originally described and named, they also may have historical significance. Type sections for two formations occur within the park: the Point Reyes Conglomerate and the Olema Creek Formation (table 7). Another two are in Golden Gate NRA: the Merced Formation and Millerton Formation (table 7).

The NPS Geologic Resources Division is developing a database of designated type sections in parks across the country. As of May 2017, three national recreation areas—Santa Monica Mountains (California), Delaware Water Gap (Pennsylvania and New Jersey; see GRI report by Thornberry-Ehrlich 2013), and Glen Canyon (Utah and Arizona; see GRI report by Graham 2016)—currently have the most type sections, each with eight. However, only a fraction of the National Park System has been investigated for type sections. The USGS "Geolex" website, http://ngmdb.usgs.gov/Geolex/search, provides location information and nomenclatural summaries for rock formations across the country.

Table 7. Type sections in Point Reyes National Seashore and Golden Gate National Recreation Area.

Note: For more information, see US Geologic Names Lexicon ("Geolex"), a national compilation of names and descriptions of geologic units, at http://ngmdb.usgs.gov/Geolex/search.

Age	Formation	Namesake	Type locality	Reference
Late Pleistocene	Olema Creek Formation	Olema Creek	*Point Reyes NS*—in Olema Creek between Boyd Stewart Ranch and Vedanta Retreat.	Galloway (1977)
Late Pleistocene	Millerton Formation	Community of Millerton	*Golden Gate NRA*—in headland northwest of Millerton.	Dickerson (1922)
Quaternary and late Pliocene	Merced Formation	Lake Merced	*Golden Gate NRA*—sea cliffs from Lake Merced, near San Francisco, to Mussel Rock about 8 mi south of Point Lobos.	Lawson (1893)
Early Eocene	Point Reyes Conglomerate of Galloway (1977)	Point Reyes Peninsula	*Point Reyes NS*—near lighthouse on west end of Point Reyes Headlands.	Galloway (1977)

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). Both types of folds can be overturned—tilted past vertical—by continued or future tectonic forces. Folds frequently "plunge" meaning the fold axis tilts. As bedrock is compressed, anticlines and synclines form adjacent to each other.

Eleven folds are identified in the park by the GRI GIS data—6 anticlines (one plunging) and 5 synclines (one plunging) (table 8; figs. 22 and 23; and poster, in pocket). Many more are mapped outside of the park (see Port 2016, GRI GIS data, and offshore geologic maps described in "Offshore Geology" section).

The overall geologic structure of the Point Reyes Peninsula is a broad, gentle syncline—termed the Point Reyes Peninsula syncline by Weaver (1949)—between the structural highs of Inverness Ridge and the Point Reyes Headlands (Galloway 1977). The axis of the syncline runs to the northwest along the west shore of Drakes Estero with the center point near the mouth of Drakes Estero. Miocene and younger sedimentary rock formations are folded by this broad syncline (Stoffer 2006). Cores from test wells for oil and gravity anomalies suggest the syncline thickens to the south under the ocean (Chapman and Bishop 1968).

Faults

A fault is a fracture in the Earth's crust along which rocks have moved. Faults are classified based on the relative motion of rocks on either side of the fault plane. The three primary types of faults are normal faults, reverse faults, and strike-slip faults (fig. 24). A strike-slip fault between two tectonic plates is called a transform boundary; the San Andreas Fault system is a network of strike-slip faults that represents a transform boundary. Thrust faults are reverse faults with a low angle (<45°) fault plane. Though the GRI GIS data reports all fault lines as "unknown offset/displacement," those that are part of the San Andreas Fault system are likely strike-slip faults (fig. 4). The GRI GIS data include 138 fault "line features" within the park boundary. Though they may not be identified as such in the data, based on location, 95 fault line features are part of the San Andreas Fault system (includes the San Andreas Fault, San Gregorio Fault, and many other unnamed faults). The remaining faults are located throughout the peninsula (table 9). A fault may exist between the Mendoza anticline and syncline, though it is not in the GRI GIS data (fig. 23). The GRI GIS data identifies many more faults which are outside of the park, particularly in the Franciscan Complex rocks in Golden Gate NRA (see Port 2016). The Marin Headlands has an especially high concentration of faults. The California Seafloor Mapping Program (see "Offshore Geology" section) identifies offshore faults, such as the Point Reyes Fault which is near but not in the park (fig. 25).

Active faults are those that have displaced rocks "recently"—in the Quaternary Period—and are therefore capable of producing earthquakes (see "Earthquakes" section). The active faults in and adjacent to the park include the San Andreas and San Gregorio Faults (see "San Andreas Fault System" section) and the Point Reyes Fault (see "Point Reyes Fault" section) (fig. 25). Displacement has occurred along the San Andreas Fault in the last 200 years, along the San Gregorio Fault in the last 11,700 years, and along the Point Reyes Fault in the last 2.58 million years (Jennings and Bryant 2010). The remaining faults in

Table 8. List of folds in the GRI GIS data mapped in Point Reyes National Seashore

*"Map Units Crossed" indicates which geologic units the fold crosses at the surface. More units may be crossed by the fold at depth.

Fold type/ name	Orientation	Plunging?	Length	Location	Map units crossed*	Description
syncline	NW–SE	Yes, northwest	4,478 m (2.783 mi)	Double Point	Qls, Qmst, Tsc	Well exposed in the Santa Cruz Mudstone at the toe of the Palomarin slide near Double Point. The axis of the syncline is marked by Alamere Falls (fig. 22).
anticline	NW–SE	Yes, northwest	2,873 m (1.785 mi)	Point Resistance	Qtmr, Qmst, Tsc, Tsm, Tm	Fold is difficult to discern because beds of the Monterey Formation are already contorted.
Point Reyes syncline	N–S	No	5,078 m (3.155 mi)	West shore of Drakes Estero	Tps	Broad, gentle syncline which defines the overall geologic structure of the Point Reyes Peninsula.
Mendoza anticline	NW–SE	No	1,747 m (1.086 mi)	Southwest of Drakes Beach	Tps	Parallel and adjacent to the Mendoza syncline. Reflects vertical faulting in the granitic basement under the Purisima Formation (Galloway 1977). The southwest limb of the anticline is much steeper (40°) than the northwest limb (5°) (fig. 23).
Mendoza syncline	NW–SE	No	1,464 m (0.910 mi)	Southwest of Drakes Beach	Tps	Parallel and adjacent to the Mendoza anticline. Reflects vertical faulting in the granitic basement under the Purisima Formation (Galloway 1977) (fig. 23).
syncline	NW–SW	No	1,444 m (0.900 mi)	Northeast of Drakes Estero	Tsm	Parallel and adjacent to an anticline.
anticline	NW–SE	No	2,266 m (1.408 mi)	Northeast of Drakes Estero	Tsm, Tm	Parallel and adjacent to a syncline.
anticline	NE–SW	No	1,047 m (0.651 mi)	Head of Schooner Bay	Tm	Fold axis extends into the valley north of Schooner Bay.
anticline	NW–SE	No	1,625 m (1.010 mi)	East of Abbots Lagoon	Tm	The hill which divides Abbots Lagoon may be a topographic expression of this anticline (Galloway 1977).
anticline	W–E	No	439 m (0.273 mi)	Kehoe Beach	Tls	Parallel and adjacent to a syncline. Two faults are just north of and parallel to the folds at Kehoe Beach (see "Faults" section) (fig. 15).
syncline	W–E	No	593 m (0.368 mi)	Kehoe Beach	Tls, Tm	Parallel and adjacent to an anticline. Two faults are just north of and parallel to the folds at Kehoe Beach (see "Faults" section) (fig. 15).

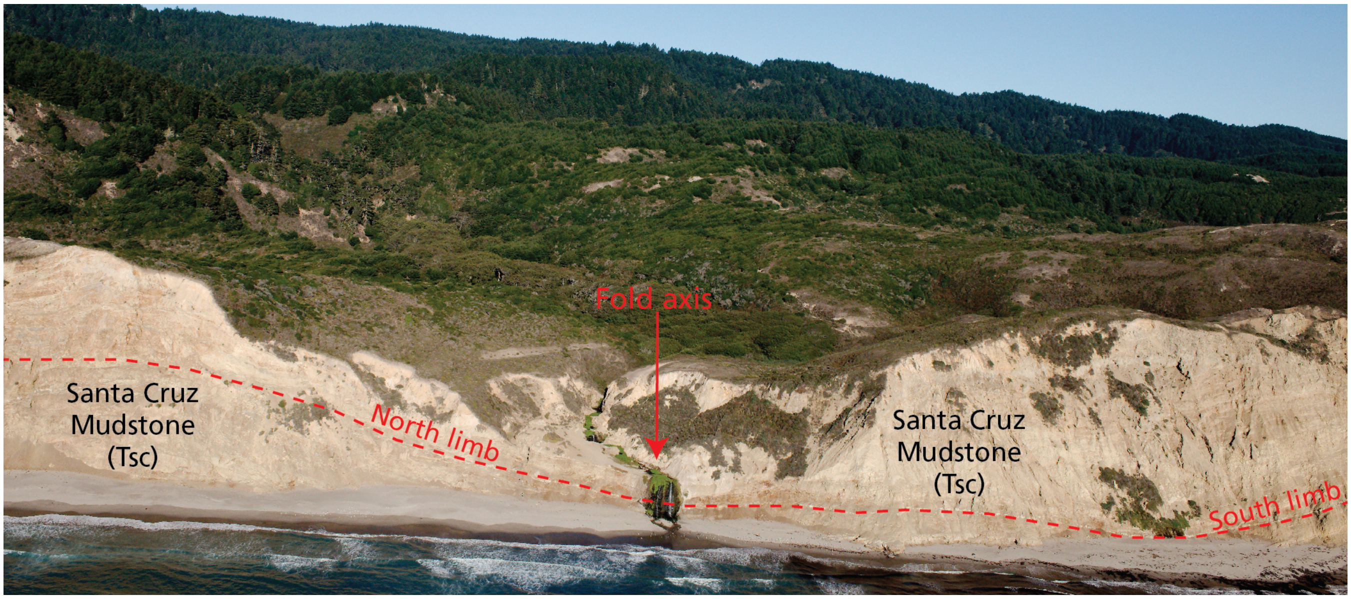


Figure 22. Photograph of plunging syncline north of Double Point.
Layers of Santa Cruz Mudstone (Tsc) are folded into a broad northwest-plunging syncline near Palomarin Beach. The fold axis, marked by Alamere Falls, intersects the coast north of Double Point. Because the fold is so broad, the u-shaped cross section (red dashed line) is difficult to discern on a single photograph, however, the north and south limbs are inclined toward the lowest point of the fold (the fold axis). View is to the east. Photograph copyright © 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org, taken 27 September 2013, used with permission.

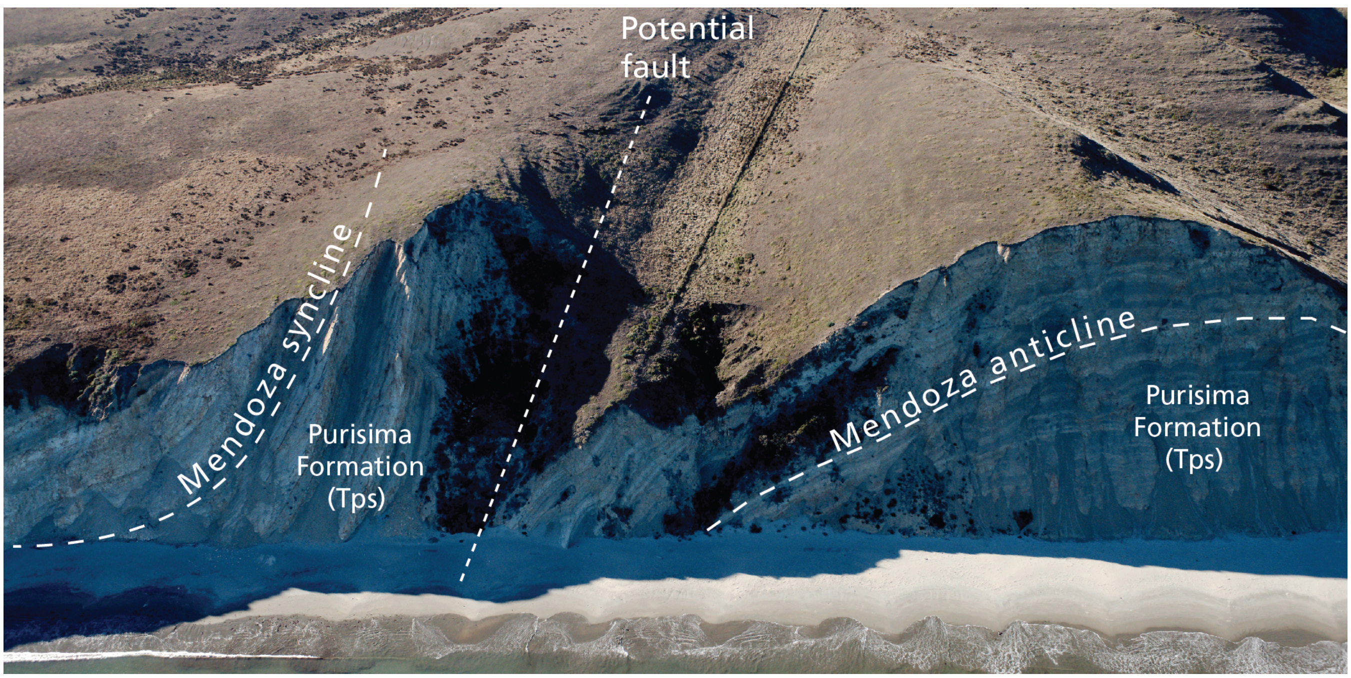
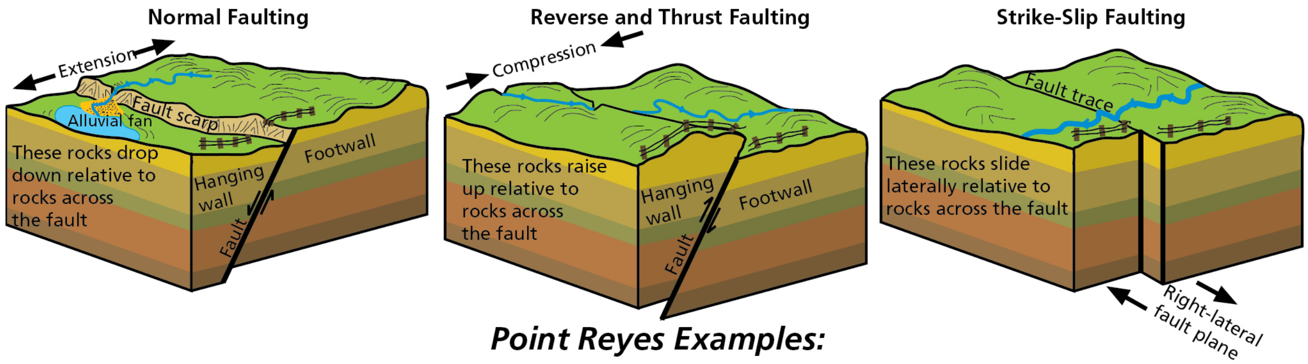


Figure 23. Photograph of the Mendoza syncline and anticline.
The Mendoza syncline and anticline are exposed in cliffs of the Purisima Formation on Drakes Beach. These folds may have been caused by blind faulting (faults that do not intersect Earth's surface) deep in granitic basement rocks. The folds appear to be offset by a fault, though no fault is mapped here in the GRI GIS Data. View is to the northwest. Photograph copyright © 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org, taken 27 September 2013, used with permission.



Point Reyes Examples:

Normal Faulting	Reverse and Thrust Faulting	Strike-Slip Faulting
none mapped in GRI GIS data	Point Reyes Fault	San Andreas Fault San Gregorio 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 at the boundary of tectonic plates is called a transform fault. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Table 9. Faults in Point Reyes National Seashore from the GRI GIS data, excluding the San Andreas Fault system.

Note: Each fault may be associated with multiple "line features" in the GRI GIS data. They have been grouped here for clarity.

*"Map Units Crossed" indicates geologic units the fault crosses at the surface; more may be crossed at depth.

Location (approximate)	Length	Map Units Crossed*	Fault Type	Notes
McClures Beach	297 m (974 ft) (0.18 mi)	Kgri	Not reported	None
Kehoe Beach	347 m (1140 ft) (0.22 mi) 1,161 m (3809 ft) (0.72 mi)	Tls, Kgri	Reverse	A high-angle reverse fault is exposed in the beach cliff (fig. 15). The massive beds of Laird Sandstone (Tls) are offset by about 40 meters. The fault trace creates an escarpment in the pastures above the sea cliff (Stoffer 2006). Kgri displays evidence of ancient and pre-Quaternary faulting (Stoffer 2006). Related to uplift of Tomales Point; other minor faults occur in the area that are too small to map (Galloway 1977). Two folds are mapped just south of these faults (see "Folds" section).
Point Reyes Headlands	808 m (2,650 ft) (0.50 mi)	Tsm, Tpr, Kg	Not reported.	Separates Tertiary marine rocks from Salinian basement. More faults exist here than are shown on the map (Galloway 1977). Though fault type was not reported, based on rock relationships, faults are likely some combination of normal and reverse, not strike-slip.
Point Reyes Headlands	730 m (2,395 ft) (0.45 mi)	Tps, Tpr, Kg	Not reported	Separates Tertiary marine rocks from Salinian basement. More faults exist here than are shown on the map (Galloway 1977). Though fault type was not reported, based on rock relationships, faults are likely some combination of normal and reverse, not strike-slip.
Point Reyes Headlands	436 m (1,430 ft) (0.27 mi)	Tsm, Tps, Tpr, Kg	Not reported	Separates Tertiary marine rocks from Salinian basement. More faults exist here than are shown on the map (Galloway 1977). Though fault type was not reported, based on rock relationships, faults are likely some combination of normal and reverse, not strike-slip.

Location (approximate)	Length	Map Units Crossed*	Fault Type	Notes
Inverness Ridge	398 m (1306 ft) (0.25 mi)	Kgri, MZPZmx	Not reported	None
Coast Campground	1,568 m (5,144 ft) (0.97 mi)	Tsm, Tm	Not reported	None
Between Palomarin and Five Brooks	5,994 m (19,665 ft) (3.7 mi)	Tsc, Tsm, Tm	Not reported	None
Between Palomarin and Five Brooks	2,896 m (9,501 ft) (1.8 mi)	Tsc, Tsm, Tm	Not reported	None
Between Palomarin and Five Brooks	5,428 m (17,808 ft) (3.4 mi)	Tsc	Not reported	None

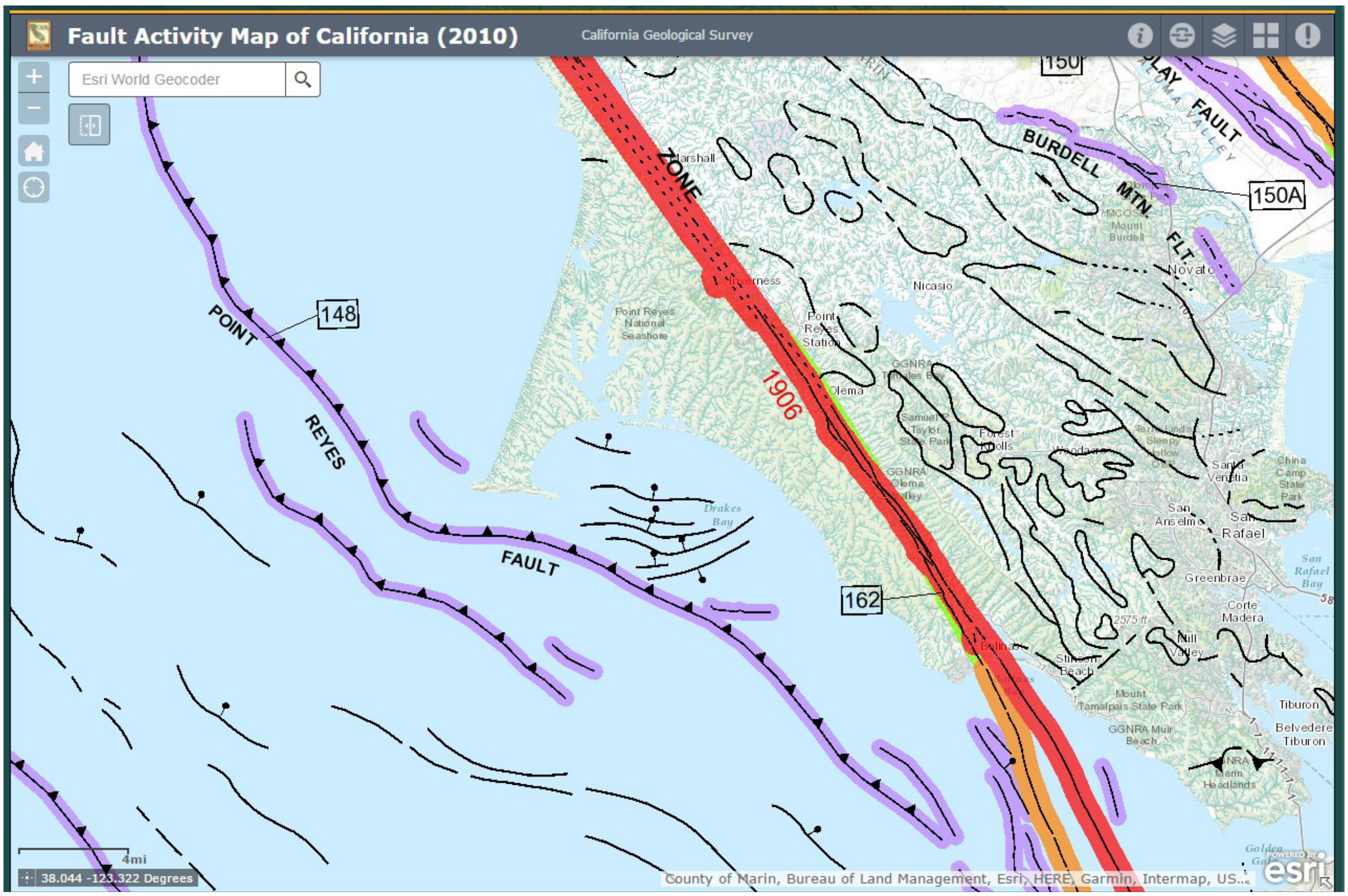


Figure 25. Map of active faults near Point Reyes National Seashore.
Faults near the park that have shown Quaternary displacement are the San Andreas (red) and San Gregorio (orange) strike-slip faults, and the Point Reyes thrust Fault (purple). The red color of the San Andreas indicates displacement in the last 200 years, and the orange (San Gregorio Fault) indicates Holocene (last 11,700 years) displacement. The purple color of the Point Reyes Fault indicates displacement during the Quaternary Period (last 2.58 million years), but the age is not further refined. The side with the triangles has moved up relative to the side without triangles. Graphic created using USGS and California Geological Survey (2010) data with the California Geological Survey fault activity map viewer, available at http://maps.conservation.ca.gov/cgs/fam/.

the park (table 9) do not show evidence of Quaternary displacement and are therefore unlikely to produce earthquakes.

San Andreas Fault System

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 state of California. It is one of the most active strike-slip faults on the planet (Hirth and Guillot 2013). The San Andreas Fault 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 represents a transform boundary between the Pacific plate (moving northwest) and the North American plate (moving southeast) (see "Geologic Setting" section). In the San Francisco Bay Area, the Point Reyes Peninsula, Monterey, Santa Cruz, and Pacifica, are on the Pacific plate (west of the fault), whereas San Jose, San Francisco, and San Rafael are on the North American plate (east of the fault). The fault juxtaposes Cretaceous granitic basement rock (see "Cretaceous Granitic Rocks" section) with the Jurassic and Cretaceous Franciscan Complex (see "Franciscan Complex" section).

Although the plate boundary is often considered to be the San Andreas Fault, it is actually a large network of northwest-trending, right-lateral strike-slip faults that cut across south and central California. This network is called the San Andreas Fault system and it includes several long, formally named faults such as the San Andreas [1,350 km (840 mi)], San Gregorio [241 km (150 mi)], and Hayward [66 km (41 mi)] as well as hundreds of smaller, unnamed faults (fig. 26). Today, the Point Reyes Peninsula is moving northwest along the San Andreas Fault. Geologic evidence, however, indicates the San Gregorio Fault sliced the peninsula off from near Point Lobos in Monterey County about 10–11 MYA (after late Miocene time) and transported it to its current position (Clark et al. 1984; Dickinson et al. 2005). Prior to that time the peninsula and Point Lobos were moving north as a unit along other faults of the San Andreas system (see "Geologic History" section).

In some places in California, the San Andreas Fault system occupies a wide zone up to 100 to 300 km (60 to 190 mi) across (Ellsworth 1990). Adjacent to the park, however, the zone runs through Olema Valley and is only about 2.4 km (1.5 mi) wide (KellerLynn 2008). South of the park (near Bolinas) the Golden Gate, San Andreas, Potato Patch, and San Gregorio faults merge into the narrow fault zone that extends north through Olema Valley and under Tomales Bay (Bruns et al. 2002; Stoffer 2006; Cochrane et al. 2015). These faults occur offshore in places, and as such are not all included in the GRI GIS data (see "Offshore Geology" section).

Figure 26. Map of the major branches of the San Andreas Fault system in central California. The boundary between the Pacific and North American tectonic plates is actually a network of large and small faults, including the San Andreas Fault. Today the Point Reyes Peninsula is along the San Andreas Fault. Geologic evidence indicates the peninsula was transported to its current location along the San Gregorio Fault. USGS graphic by Darrell G. Herd, available at https://pubs.usgs.gov/gip/earthq3/where2.html.

Most of the faults of the San Andreas system are active. The system creates significant seismic hazards and risk (see "Earthquake Probability, Hazards, and Risk" section). Movement causes both rapid seismic shaking (see "Earthquakes" section) and aseismic creep (without shaking). All of the faults are believed to be seismically connected even if they do not intersect; movement along one could trigger movement in another and/or stress from one fault could be absorbed by another. The nature of these connections is not well

understood and is currently the subject of ongoing research.

Evidence suggests lateral displacement began along the San Andreas Fault system about 30 million years ago in southern California and reached the San Francisco Bay Area between 15 million to 12 million years ago (Atwater 1970, 1989; Page and Wahrhaftig 1989, Stoffer 2006; see "Geologic History" section). The San Andreas Fault alone is estimated to be moving approximately 14 mm (0.55 in) per year (Irwin 1990). But in the area of the park, the estimated displacement is even higher, about 17 to 30 mm (0.7 to 1.2 in) per year (Bryant and Lundberg 2002; Grove and Niemi 2005). This is due to the addition of right-slip along nearby faults including about 4 to 13 mm (0.2 to 0.5 in) per year along the San Gregorio Fault (Weber and Lajoie 1977; Clark et al. 1984; Clark 1998; Bruns et al. 2002).

Not all of the motion along the San Andreas Fault system is lateral, many of the faults in the system display some component of vertical motion, both up (compression) and down (extension). Where a right-lateral fault bends to the left, compression and uplift, often involving thrust faults, occurs (Will Elder, Golden Gate National Recreation Area, park ranger, written communication, 30 October 2015). Where a right-lateral fault bends right, extension and down-dropped areas form valleys (Sloan 2006). Today, about 90% of the movement along the San Andreas Fault is lateral and 10% is vertical motion (Sloan 2006). Compression along the San Andreas Fault resulted in the formation of the Point Reyes Fault (described in next section) and the Point Reyes syncline, which uplifted the Point Reyes Peninsula (Hansen and Grove 1996).

Point Reyes Fault

A large north- and east-dipping reverse fault—the Point Reyes Fault—runs offshore near the Point Reyes Headlands and is probably responsible for ongoing uplift of the headlands region (fig. 25; Grove et al. 2010; Johnson et al. 2015). It is a thrust fault—reverse fault with a low angle (<45°) fault plane—that has predominantly north-side-up motion (Hoskins and Griffiths 1971; McCulloch 1987; Heck et al. 1990) and likely connects at depth with the San Gregorio Fault to the south, which means that it is part of the San Andreas Fault system (Ryan et al. 2008). Because it is offshore, it was not included in the GRI GIS data. It is, however, included on the offshore map by Watt et al. (2015b); see the "Offshore Geology" section for more information. Vertical motion on a submerged fault, such as the Point Reyes Fault, has the potential to generate tsunamis during an earthquake (see "Tsunamis" section).

The fault is considered "blind" because it does not intersect Earth's surface. Understanding is therefore based on seismic profile records completed in the 1960s through the 1980s by oil exploration companies (Watt et al. 2015b). Different types of rock reflect sound pulses differently. Because the Point Reyes Fault juxtaposes granitic basement and sedimentary rocks, the seismic profile reflects this transition thereby delineating the fault (fig. 27).

The Point Reyes Fault shows signs of movement extending from late Miocene time to the Quaternary (Jennings and Bryant 2010). Some researchers think the fault is still active (Stoffer 2006, Grove et al. 2010), but it is generally agreed that movement has ceased or slowed since about 21,000 years ago (Watt et al. 2015b). Since late Miocene time, the fault has displaced granitic basement rocks vertically by at least 1.4 km (0.9 mi) (McCulloch 1987). Elevated marine terraces and ancient alluvial and coastal dune deposits indicate the peninsula has been rising through at least part of the Quaternary (see "Coastal Resources" section; Stoffer 2006). This uplift combined with west-side-up movement on the San Andreas Fault (Grove and Niemi 2005) resulted in uplift of the Point Reyes Peninsula, including Tomales Point and the adjacent continental shelf (Johnson et al. 2015). Basement rocks, Tertiary marine sedimentary rocks, and the Point Reyes syncline have all been uplifted and deformed along the Point Reyes Fault, forming the present-day Point Reyes peninsula (Weaver 1949; McCulloch 1987; Watt et al. 2015b). Current uplift rates are estimated by Grove et al. (2010) and Rus Graymer (USGS, geologist, comment during 2007 GRI scoping meeting) to be as much as 1 mm (0.04 in) per year. Jennings and Bryant (2010), however, report less than 0.2 mm (0.008 in) per year. These differences are likely because different areas of the peninsula are or were rising at different rates.

Fault Topography

The park contains textbook examples of topography which resulted from movement along faults. Perhaps the most apparent example is the linear valley directly above the San Andreas Fault, occupied by Bolinas Lagoon, Olema Valley, and Tomales Bay. Rocks along the fault were "ground up" due to the tectonic stresses, making them weak and easily eroded into valleys (Sloan 2006). Surface rupture—an offset of the ground where a fault intersects Earth's surface—is another obvious product of fault activity (see "Earthquakes" section). Though surface rupture may become obscured by erosion and vegetation over time, such as that from the 1906 earthquake, displaced structures may still remain visible as evidence of fault motion. Fence posts along the Earthquake Trail were positioned to demonstrate the offset observed following the 1906 earthquake (fig. 28).

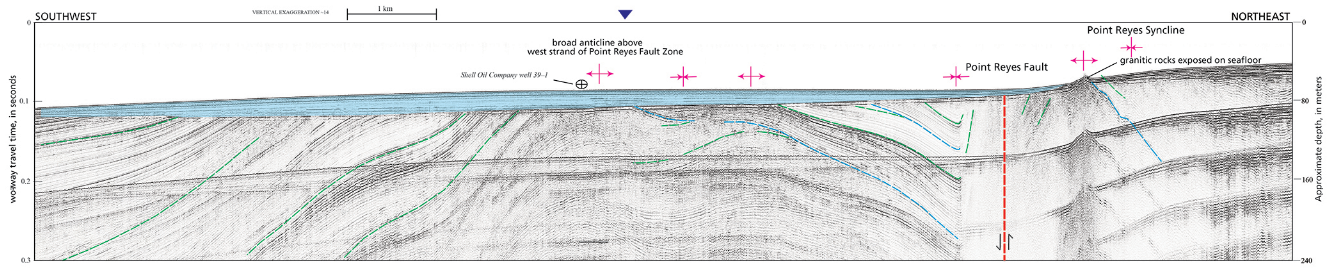


Figure 27. Seismic profile of the Point Reyes Fault.
A seismic profile is a cross section showing the way different rock layers reflect sound waves. A fault can be inferred where different rock types appear to be offset. Reverse faults are easiest to detect on a seismic profile because they have vertical (up and down) motion. The Point Reyes Fault has predominantly north side up motion and is a "blind" thrust fault—the fault plane does not intersect the ocean floor. It is covered by layers of inferred uppermost Pleistocene and Holocene shelf strata (blue) which were deposited since last sea-level lowstand about 21,000 years ago (Watt et al. 2015a). Graphic modified from a USGS graphic in Watt et al. (2015a, Sheet 8).

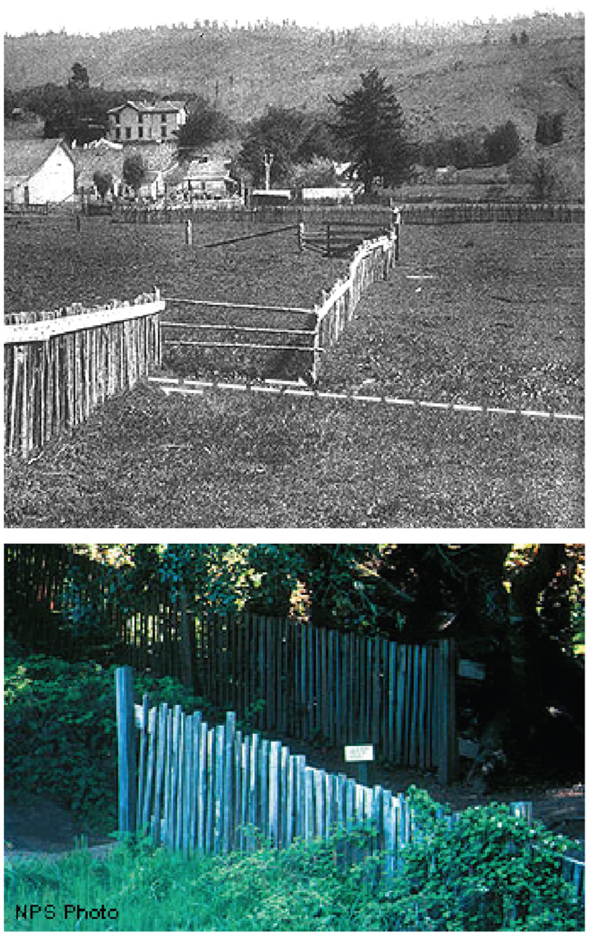


Figure 28. Photographs of surface rupture.
Fences are obvious evidence of fault movement. Top photograph: a fence near Bolinas offset by the 1906 earthquake; by G. K. Gilbert (in Lawson 1908). Lower photograph: a reconstruction of fence offset along the Earthquake Trail in the park; NPS photograph.

Classic fault topography also includes fault scarps, sag ponds, shutter ridges, and drainage anomalies. Fault scarps and sag ponds occur between Olema and Bolinas Lagoon (Stoffer 2006). Fault scarps are low, linear ridges that show where movement has occurred. Sag ponds form where fault movement impounds stream drainage causing water to pool in the depressed area created along the fault. These are classic lacustrine features of the San Andreas Fault zone (see "Lacustrine Features" section). Shutter ridges form where lateral fault movement crosses a series of ridges of valleys thereby "shutting in" valleys with portions of displaced ridges (fig. 29). A shutter ridge is identified along the Earthquake Trail and topographic maps reveal many more between Inverness Park and Five Brooks (fig. 30). As the Point Reyes Peninsula moved, Inverness Ridge became a large shutter ridge and diverted all the streams coming off it northward into Olema Valley drained by Olema Creek and ultimately Tomales Bay (Stoffer 2006).

Movement along faults and the creation of scarps, sag ponds, and shutter ridges creates drainage anomalies where streams are diverted down paths they would not otherwise carve. The name of the town "Five Brooks" speaks to the conspicuous nature of local stream drainages. Many examples of stream diversion due to fault movement occur in the park in the San Andreas Fault zone. Near the Bear Valley Visitor Center, Bear Valley Creek makes a sharp right turn to the northwest where it reaches the fault trace (and shutter ridge) of the 1906 surface rupture (fig. 30). North of Bolinas, Pine Gulch Creek and Olema Creek run in opposite directions for nearly 2 miles on opposite sides of a ridge, though they occur at the same elevation and would be expected to flow in the same direction. Each of these streams has eroded its course in an old fault trace—Pine Gulch Creek on the southwest side of

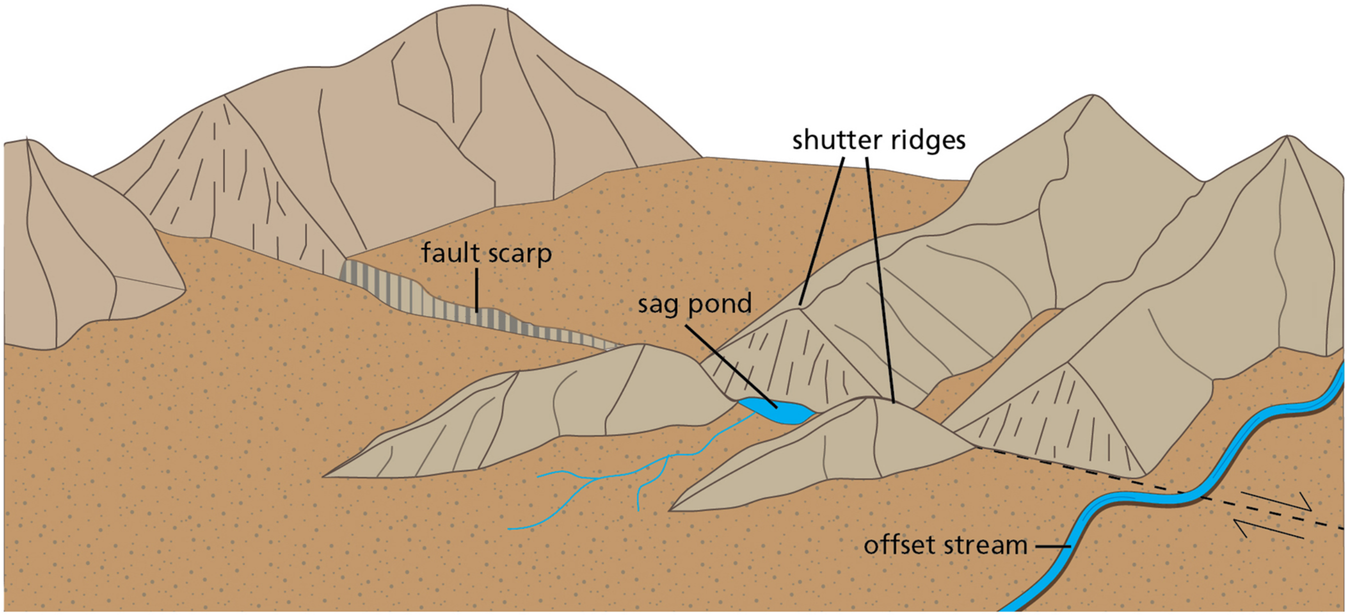


Figure 29. Illustration of displacement topography features.
Lateral displacement along faults creates a unique set of topographic features. Where movement disrupts the Earth's surface a fault trace, scarp, or eventually a linear valley may form. Water may collect in low lying areas along the fault line forming sag ponds. A ridge that has been displaced by fault movement and subsequently "shuts in" an adjacent valley is called a shutter ridge. Streams or drainage channels which cross the fault may become abruptly offset. The dashed line shows the trace of the fault and the arrows show the direction of relative motion. NPS graphic by Rebecca Port modified from Research Group for Active Faults of Japan (1991).

the San Andreas Fault zone and Olema Creek on the northeast side (Gallow 1977). Several streams in the park also make sharp and unexpected turns based on topography and geology (e.g., Arroyo Honda, Alamea Creek, the central portion of Bear Valley Creek) (Galloway 1977). Lagunitas and Nicasio creeks are offset streams that were diverted northward into Olema Valley (Stoffer 2006). These drainage anomalies can be used to pinpoint the location of underlying faults and as evidence of fault activity (Hansen and Grove 1996).

Earthquakes

Some of the movement along faults in and near the park is imperceptibly slow ("creep") while others have been in leaps and bounds. Earthquakes are ground vibrations—shaking—that occur when rocks suddenly move along a fault, releasing accumulated energy (Braile 2009). Earthquake severity can be measured by intensity or magnitude. Earthquake intensity ranges from imperceptible by humans (intensity I) to total destruction of developed areas and alteration of the landscape (intensity XII). The "Richter magnitude" is a measure of the energy released by an earthquake on a base-10 logarithmic scale. Earthquakes can directly damage park infrastructure, or trigger other hazards such as slope movements that may impact park resources, infrastructure, or visitor safety. Braile (2009), the NPS Geologic Resources Division Seismic Monitoring website (http://go.nps.gov/seismic_monitoring), and the USGS Earthquakes Hazards website (http://earthquake.usgs.gov/) provide more information.

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 to property and loss of life in the San Francisco Bay Area: (1) the 1868 Hayward fault earthquake (maximum intensity IX; estimated magnitude 6.8), (2) the 1906 San Francisco earthquake (maximum intensity XI; estimated magnitude 7.9), (3) the 1989 Loma Prieta earthquake (maximum intensity IX; estimated magnitude 6.9), and (4) the 2014 South Napa earthquake (maximum intensity VIII; estimated magnitude 6) (Boatwright and Bundock 2008; USGS 2017).

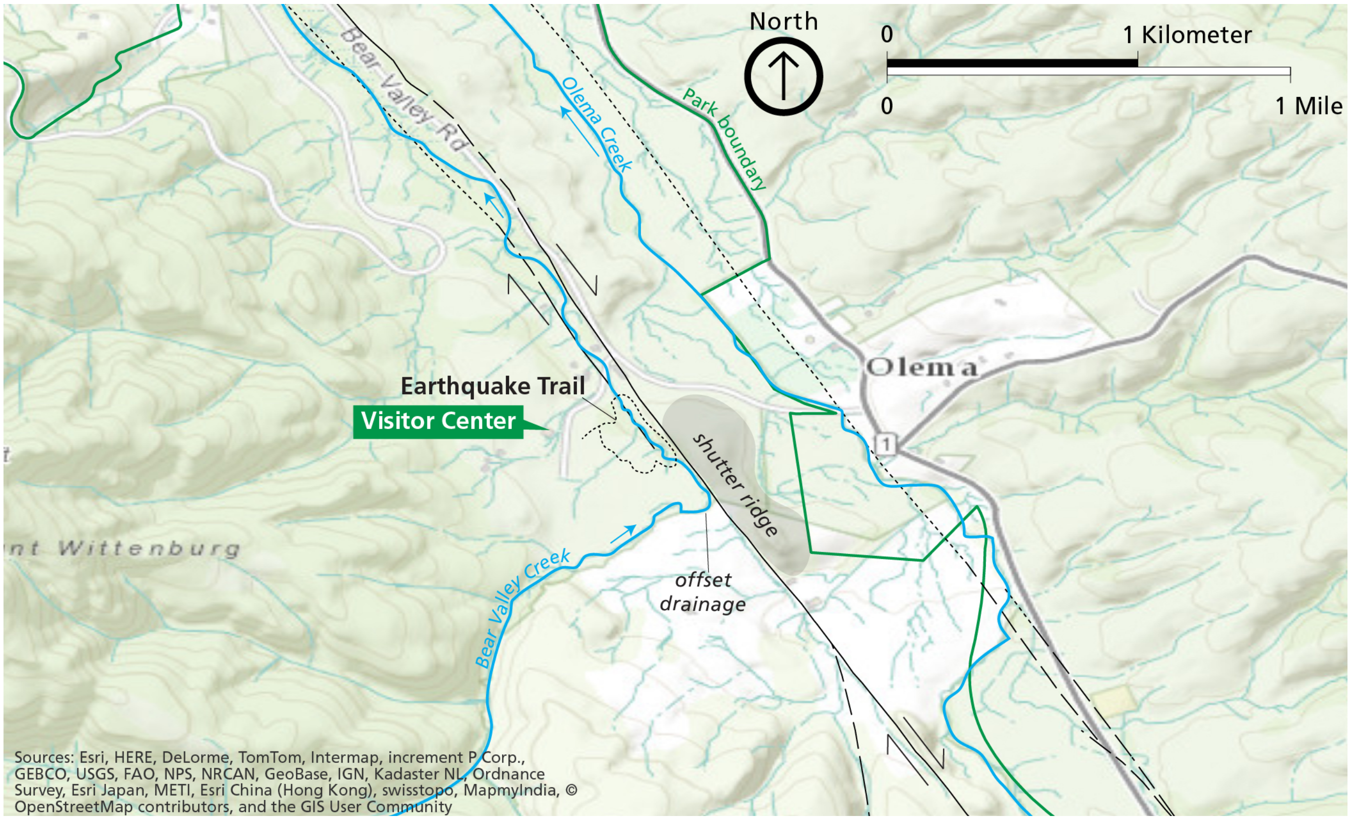


Figure 30. Examples of fault topography in the park.
The long, linear valley which runs through the town of Olema formed because rocks broken up by fault movements eroded more easily than the surrounding rock. It is the most apparent regional evidence of lateral fault displacement. Locally, features such as a shutter ridge and offset drainage channel are observable along the Earthquake Trail near the park's visitor center. Bear Valley Creek probably once flowed northeast all the way to reach Olema Creek. Fault movement shifted Bear Valley Creek northwest (black half arrows) which blocked the drainage with a shutter ridge, forcing the creek to make an abrupt turn to follow the path of least resistance. Today the creeks are parallel and both flow toward Tomales Bay. Faults are shown as black lines (dashed where approximate, short dashed where inferred). NPS graphic annotated by Rebecca Port using GRI GIS data with base map sources indicated on graphic.

One of the most spectacular effects of large earthquakes is surface rupture (USGS 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 (USGS 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.

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. 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 Earthquake Trail near Bear Valley Visitor Center is a classic place to see the effects of the 1906 earthquake. In the earthquake, the Point Reyes peninsula lurched nearly 6 m (20ft) to the northwest in less than a minute. Blue posts along the Earthquake Trail mark the 1906 ground rupture, a fault scarp and shutter ridge are visible, and a reconstructed fence shows the offset created during the quake. Movement during the destructive quake is thought to have originated on the San Andreas Fault about 60 km (37 mi) to the south, offshore of San Francisco (Bolt 1968; Lomax 2005). However, the location of maximum known movement on the San Andreas Fault during the 1906 earthquake was in the area of the park (Lawson 1908).

Trench excavations by Neimi and Hall (1992) indicated that the recurrence interval for large earthquakes in the area of the park is in the range of 221±40 years. Johnson et al. (2015) noticed a lack of small earthquakes on the San Andreas Fault since the devastating 1906 earthquake. This could indicate that another significant quake may occur in the near future (see "Earthquake Probability, Hazards, and Risks" section).

Landslides

Slope movements are the downslope transfer of soil, regolith, and/or rock under the influence of gravity. Soil creep, rockfalls, slumps, debris flows, and avalanches are all types of slope movements. These processes and the resultant deposits (**Qls**) are known as "mass wasting" and commonly grouped as "landslides." In general, landslides occur on steep slopes and in weak rocks on time scales ranging from seconds (rapid) to years (gradual) (Clague 1969, Wills et al. 2011). Refer to figure 31 for schematic illustrations of landslide types. Landslides become hazards if there is risk to life, property, or other resources. Determining landslide susceptibility and addressing landslide hazards is covered in the "Geologic Resource Management" section.

Rockfalls occur regularly in the park. A rockfall consists of the rapid, free falling movement of detached rock. Many of the cliffs and bluffs within the park are composed of friable rocks and are unstable. Small coastal slope movements, such as the tumbling of boulders and rocky debris down cliffs are probably quite common, though rarely witnessed. Prominent documented rockfalls in the park include the March 2015 collapse of a portion of Arch Rock and the January 2017 bluff collapse at the northern end of Tomales Point (fig. 32). The Arch Rock collapse claimed one life and injured another. Multiple agencies responded to the Arch Rock collapse and the NPS Geologic Resources Division prepared a risk assessment and cliff collapse monitoring report that included management recommendations (see "Landslide Hazards" section; Bilderback 2015). The Tomales Point bluff collapse took a portion of the trail with it (fig. 32). In December 2015, a visitor reported cracks on a portion of the bluff near the Chimney Rock Trail which indicates instability and the potential for slope movements in the near future.

Slumps also occur regularly in the park. A slump is when a mass of rock or loosely consolidated material slides along a curved or planar surface. The rate of movement in a slump and depth of rock or soil affected varies widely. Shallow slumps—generally those less than 3–5 m (10–15 ft) in depth—tend to move rapidly, while deep-seated slumps—generally those greater than 3–5 m (10–15 ft) in depth—typically proceed more slowly. Evidence of slumps, such as tilted trees and closed depressions, are quite common throughout the park. Slumps are especially abundant within the Santa Cruz Mudstone near Double Point (fig. 33).

Debris flows have been documented in the park during floods (KellerLynn 2008). A debris flow is a water-laden mass of rock, soil, and mud that can flow almost as fluidly as water. Debris flows move rapidly and can be highly mobile over long distances. They are not as common in the park as rockfalls and slumps but have the potential to cause significant damage if they do occur (see "Landslide Hazards" section).

Large landslide deposits (**Qls**) and the direction of major slope movements are included in the GRI GIS data. They are mapped in a few areas along Inverness Ridge and a large area along the coast near Double Point (see poster, in pocket). However, the landslides shown on bedrock maps are often less than 20% of the actual coverage. Geologists intentionally do not include all landslide deposits on bedrock geologic maps; they are typically included only if the deposit is massive and obscures bedrock. Therefore the areas mapped as landslides represent a fraction of their actual number and extent (Chris Wills, geologist, California Geological Survey, scoping meeting, 27 September 2007).

The large area [at least 6.4 km- (4 mi-) long and 1.6 km- (1 mi-) wide, (Galloway 1977)] of landslide deposits (**Qls**) in the vicinity of Double Point consists mainly of intact to highly disrupted slumped blocks of Santa

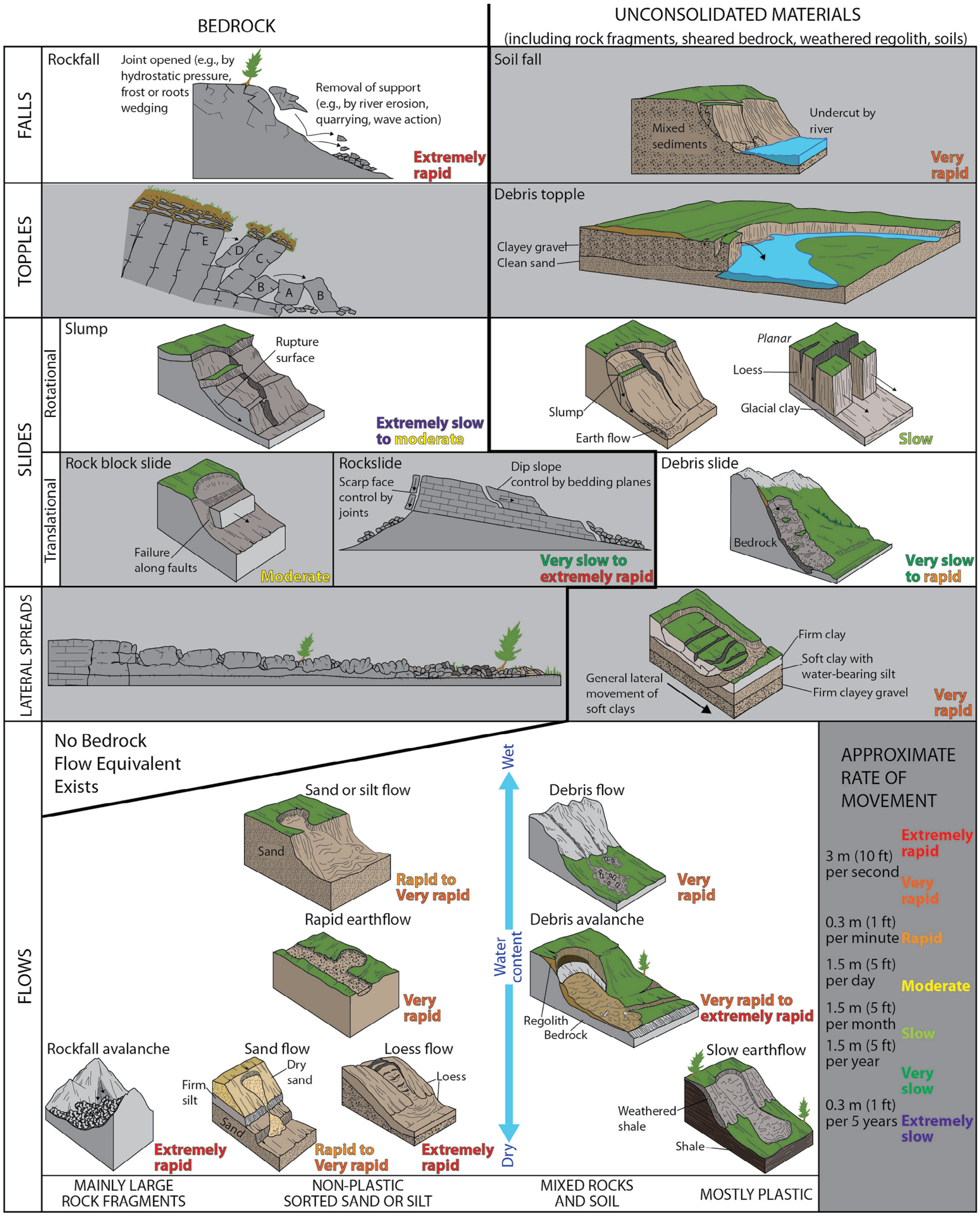


Figure 31. Graphic showing slope movements.
Different types of slope movement are defined by material, nature of the movement, rate of the movement, and moisture content. White boxes indicate slope movements that are common causes of damage in the park, though other types may occur and may also cause damage. Graphic by Trista Thornberry-Ehrlich (Colorado State University) redrafted using a graphic and information in Varnes (1978). Rates of movement are from Cruden and Varnes (1996).

Figure 32. Photographs of prominent slope movements in the park.
Prior to collapse, Arch Rock was a popular tourist destination (upper left photograph, note the people at the end of the overlook). A 12-m- (40-ft-) long fissure, 50-cm- (20-in-) wide in some sections, developed just days before the incident (lower left photograph). The fissure marks the location where the slope eventually failed. The park had posted several warning signs. In March 2015, a portion of the Arch Rock overlook collapsed, claiming one life and injuring another (upper right photograph). Fissures are present on the remaining bluff, indicating it is still unstable and more sections are likely to collapse. The park does not have plans to reopen this area. In January 2017 a section of sea cliffs on Tomales Point collapsed taking the Tomales Point trail with it. Fractures (visible across the remaining trail in the lower right photograph) indicate the cliff is still unstable. NPS photographs, except for upper left photograph copyright © 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org, taken 27 September 2013, used with permission.

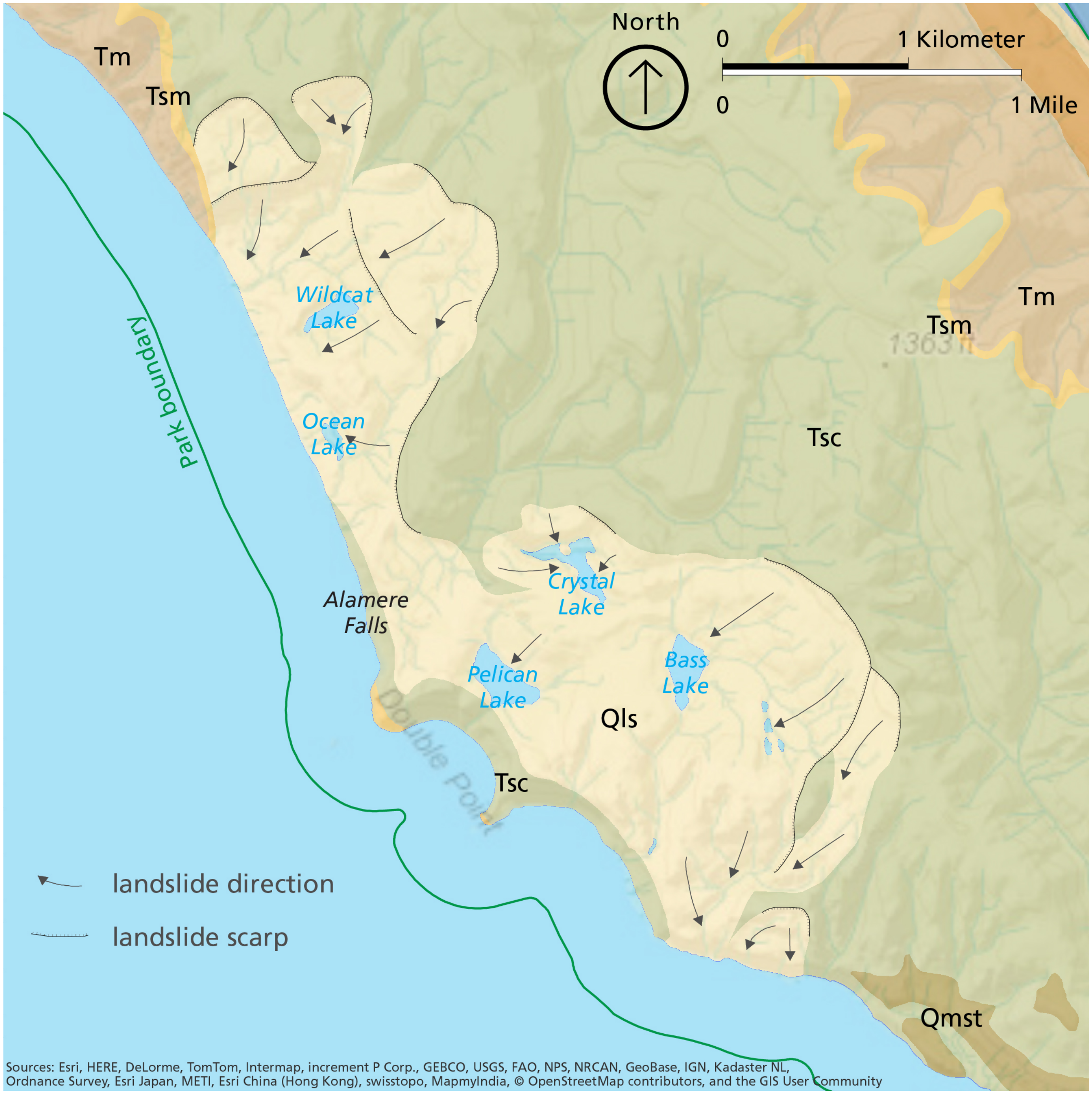


Figure 33. Map of landslides at Double Point.
In the area near Double Point, the brittle and steeply dipping Santa Cruz Mudstone (Tsc) is susceptible to slumping. Ponds formed where water pooled behind blocks of slumped mudstone. Coastal ponds are otherwise uncommon in this area. Landslide deposits (Qls) are primarily composed of blocks of Santa Cruz Mudstone (Tsc) slumped shoreward. Qmst are marine and stream terrace deposits; Tm is the Monterey Formation; Tsm is the Santa Margarita Sandstone. NPS graphic annotated by Rebecca Port using GRI GIS data with base map sources indicated on graphic.

Cruz mudstone (figs. 18 and 33; Clark and Brabb 1997). The brittle character and steep shoreward dip (about 45 °) of strata made the mudstone particularly susceptible to slumping (Stoffer 2006). These landslides have been described in detail by Clague (1969) who concluded that current topography formed in response to repeated small, earthquake-triggered displacements. The timing of events is not well constrained other than some landslides must have occurred prior to the 1906 earthquake because Gilbert (in Lawson 1908) reported "a change" in the landslide area following the quake. The amount of change in landslide area was not specified. Slumping appears to have initiated inland and propagated to the shore (Galloway 1977). Today, beach erosion removes the toe of the slide area which initiates further slide motion (Stoffer 2006). Impounded depressions behind the fallen mudstone blocks gradually filled with water, becoming freshwater lakes and wetlands (see "Lacustrine Features" section).

Lacustrine Features

Natural lakes in the park were created by geologic processes. Sag ponds formed where streams impounded by fault movements caused water to collect in depressed areas along the San Andreas Fault. As faults move, the size and shape of sag ponds change and new ponds may be created. Sag ponds are a classic topographic feature of faulted landscapes (see "Faults" section). The park contains many small sag ponds. San Andreas Lake (south of the park) is an example of a very large sag pond. Lakes also formed in association with landslides (fig. 33). In the coastal area of Double Point, a large landslide complex consists of slumped blocks of Santa Cruz Mudstone. Because mudstone is relatively impermeable, water gradually filled the depressions created when the blocks tilted and sank. Today, these freshwater lakes (and wetlands) serve as prime habitat for snakes and birds and hunting grounds for predatory mammals (KellerLynn 2008). The lakes are also important recreational resources and provide opportunities for birding, swimming, kayaking, and canoeing, and serve as hiking destinations. The February 23, 1997, edition of the San Francisco Chronicle named Bass Lake as the number one place in the Bay Area to go swimming (Ketcham 1999). In addition to natural lakes, farmers and ranchers created a hundred or more stock ponds in the park by damming streams (KellerLynn 2008). These now are important habitat for red-legged frogs (Ben Becker, Point Reyes National Seashore, science advisor, email, 10 September 2017).

Coastal Resources

Coastal natural resources are located in a transition zone between terrestrial and marine environments, and as such, include resources and characteristics of both types of environments. Coastal environments—shaped by waves, tides, wind, and geologic processes—may include tidal flats, estuaries, river deltas, wetlands, dunes, beaches, bays, barrier islands, bluffs, headlands, and rocky tidepools. The National Park Service manages 85 ocean, coastal, and Great Lakes parks with more than 18,000 km (11,200 miles) of shoreline, of which 161 km (100 mi) is in Point Reyes National Seashore (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. 2016). Management and planning for these scenarios is discussed in the "Geologic Resource Management" section. The NPS Oceans and Coasts website, http://go.nps.gov/npsoceans, provides additional information.

The coastline in the park is diverse and the landscape varies widely, from cliffs and bluffs, to sandy beaches and dunes, to bays, estuaries, and lagoons (table 10; fig. 34). Cliffs and bluffs are typically composed of Cretaceous granitic rocks and Tertiary marine rocks, while beaches and the floor of coastal water bodies are composed of Quaternary sand, silt, clay, and/or mud. The GRI GIS data only covers onshore areas. The California Seafloor Mapping Program (see "Offshore Geology" section) provides geologic information for the offshore areas, including Tomales Bay, Drakes Bay, Drakes Estero, and Estero de Limantour.

The Point Reyes Peninsula is uplifting at a rate of about 1 mm (0.04 in) per year (see "Point Reyes Fault" section; Grove et al. 2010). This uplift is likely responsible for the formation of high coastal bluffs and sea cliffs like those at the Point Reyes Headlands and along the coast north of Bolinas (fig. 16; Galloway 1977; Griggs et al. 2005). Uplift has created shallow water offshore from these areas and therefore little room for sediment accumulation (Chochrane et al. 2015). In contrast, the modern marine transgression (sea level rise) is responsible for sediment accumulation on ocean beaches and the filling of bays and lagoons (Stoffer 2006).

Ancient Coastlines

Marine terraces, drowned stream valleys, and ancient dune deposits in the park are evidence of the location of the peninsula's former coastlines. The seashore has been both higher and lower than its current position at different times throughout the Quaternary period. These relative changes in position were due to sea level change, uplift of the land, or some combination of the two.

Table 10. Coastal features and processes in Point Reyes National Seashore.

Coastal Feature	Park Example(s)	Associated Coastal Process(es)	Rock/Sediment Type	Map Units Involved/Affected
Beaches and dunes	Point Reyes Beach Drakes Beach Limantour Spit Wildcat Beach Abbotts Lagoon dunes	Erosion Longshore drift Eolian (wind) processes Tides	Sand	Qbs, Qdsy, Qobs
Bluffs and associated sea arches and stacks	Tomales Point Point Reyes headlands Chimney Rock Arch Rock Double Point	Landslides Wave erosion	Cretaceous granitic rocks Tertiary marine rocks	Kg, Kgri, Kgdt, Tpr, Tps
Bays	Tomales Bay Drakes Bay	Freshwater influence Tides	Clay, silt, and sand	See California Seafloor Mapping Program maps (Cochrane et al. 2015; Johnson et al. 2015; Watt et al. 2015a; Watt et al. 2015b)
Estuaries	Drakes Estero Estero de Limantour	Tides	Clay, silt, and sand	See California Seafloor Mapping Program maps (Cochrane et al. 2015; Johnson et al. 2015; Watt et al. 2015a; Watt et al. 2015b)
Lagoons	Abbotts Lagoon	Tides	unknown	Not mapped
Wetlands	Giacomini wetlands	Tides	Mud	Qbmo
Rocky Tidepools	Duxbury Reef	Erosion	Tertiary marine rocks	Tsc
Marine Terraces	North of Bolinas	Uplift	Tertiary marine rocks covered in Quaternary sediments	Qtmr, Qmst

Figure 34. Photograph of the coastal landscape in Point Reyes National Seashore.
The coastal landscape of the peninsula is diverse. The high cliffs and bluffs of the Point Reyes Headlands are visible in the background. Drakes Estero extends north across the peninsula from Drakes Bay (left side of photograph). Point Reyes Beach lines the coast (not visible in photograph) from the headlands north to Tomales Point. NPS photograph by Rebecca Port, taken September 2016 looking southwest from Mount Vision.

Marine terraces—uplifted wave-cut platforms—are evidence of uplift and/or formerly higher sea level. A wave-cut platform is a gently sloping rock surface that extends from the beach out into the ocean (figs. 19 and 35). It is formed by the prolonged erosive action of waves against the edge of the land during extended periods of steady sea level. Wave-cut platforms are often covered in sand; many beaches in the park are underlain by wave-cut platforms. If sea level drops or tectonic activity raises the land, the wave-cut platform becomes exposed above sea level forming a relatively flat, elevated area called a marine terrace (fig. 36). This is very common along the Pacific Coast (Pampeyan 1994). If uplift occurs repeatedly, several levels of marine terraces, each progressively older and higher, form landward of the shore (Sloan 2006). In the park, terraces occur at several levels ranging from 10 to 200 m (30 to 660 ft) above sea level (Minard 1971; Galloway 1977; Grove et al. 1995; Lajoie 1996; Clark and Brabb 1997). The youngest (lowest) marine terrace in the park formed about 82,000 years ago during a sea level highstand and prior to 330,000 years ago the Point Reyes Headlands had not yet emerged from the sea (Woodley and Grove 2010).

The youngest and most prominent marine terrace on the Point Reyes Peninsula extends from Bolinas to Estero de Limantour (figs. 16 and 35). The large terrace does not appear today as a single flat elevated area for several reasons. The terrace did not rise uniformly; uplift rates were greater in the south (Galloway 1977; Woodley and Grove 2010). Covering the terrace is a thick wedge of alluvial gravel, sand, and silt (**Qtmr**) which is being dissected by modern erosion (fig. 16). Finally, in the last 50,000 years this location could have eroded back many miles so the width of the terrace is probably only a fraction of its original extent (Galloway 1977). Another marine terrace occurs at the head of Tomales Bay and extends south through the Point Reyes Station area (Stoffer 2006).

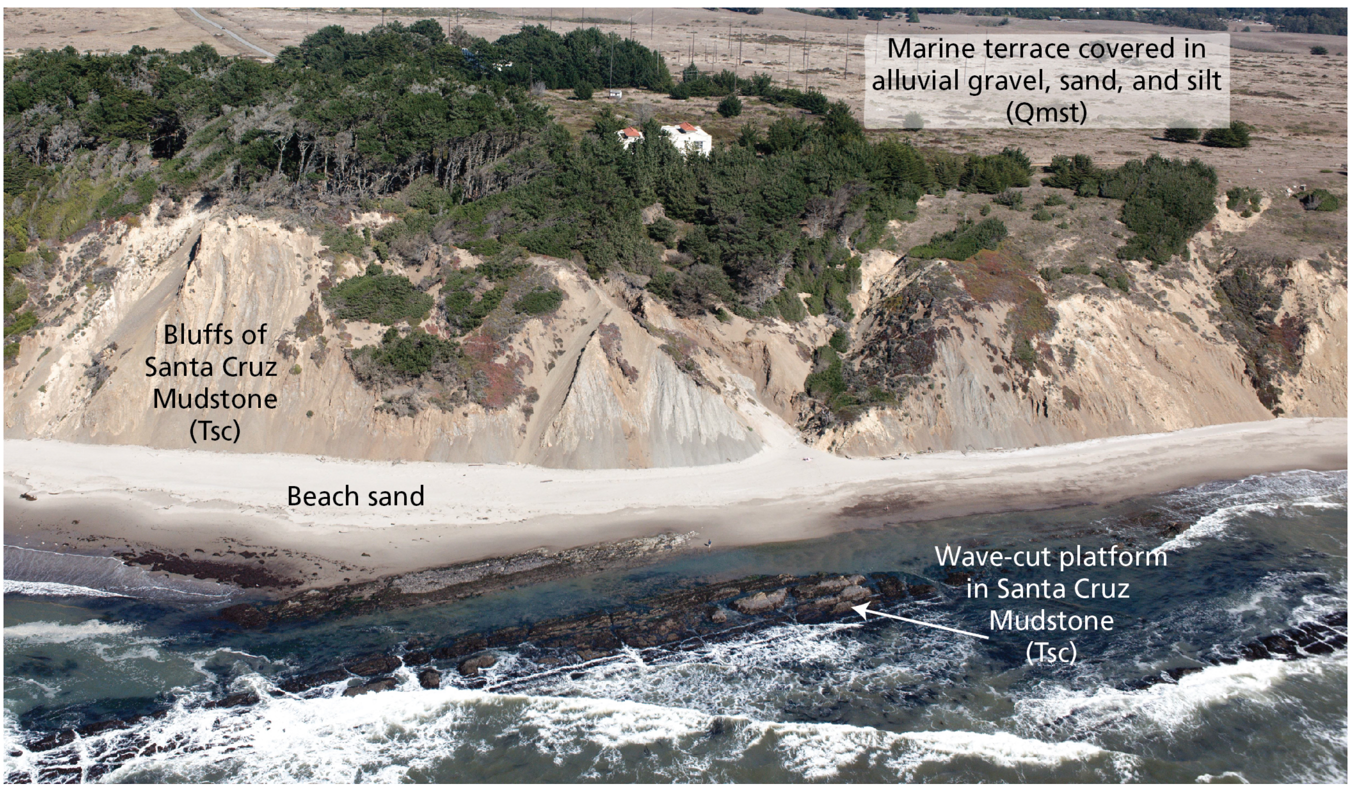


Figure 35. Photograph of a marine terrace and wave-cut platform near Palomarin.
An active wave-cut platform extends more than a half kilometer (half mile) offshore from Bolinas north to Double Point. The platform is covered by beach sand on the shore and only partially visible during low tide, as in the photograph. On top of the bluffs behind the beach is an ancient wave-cut platform—a marine terrace—which is covered in alluvial sediments. Photograph copyright © 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org, taken 1 October 2009, used with permission. Annotations by Rebecca Port (NPS).

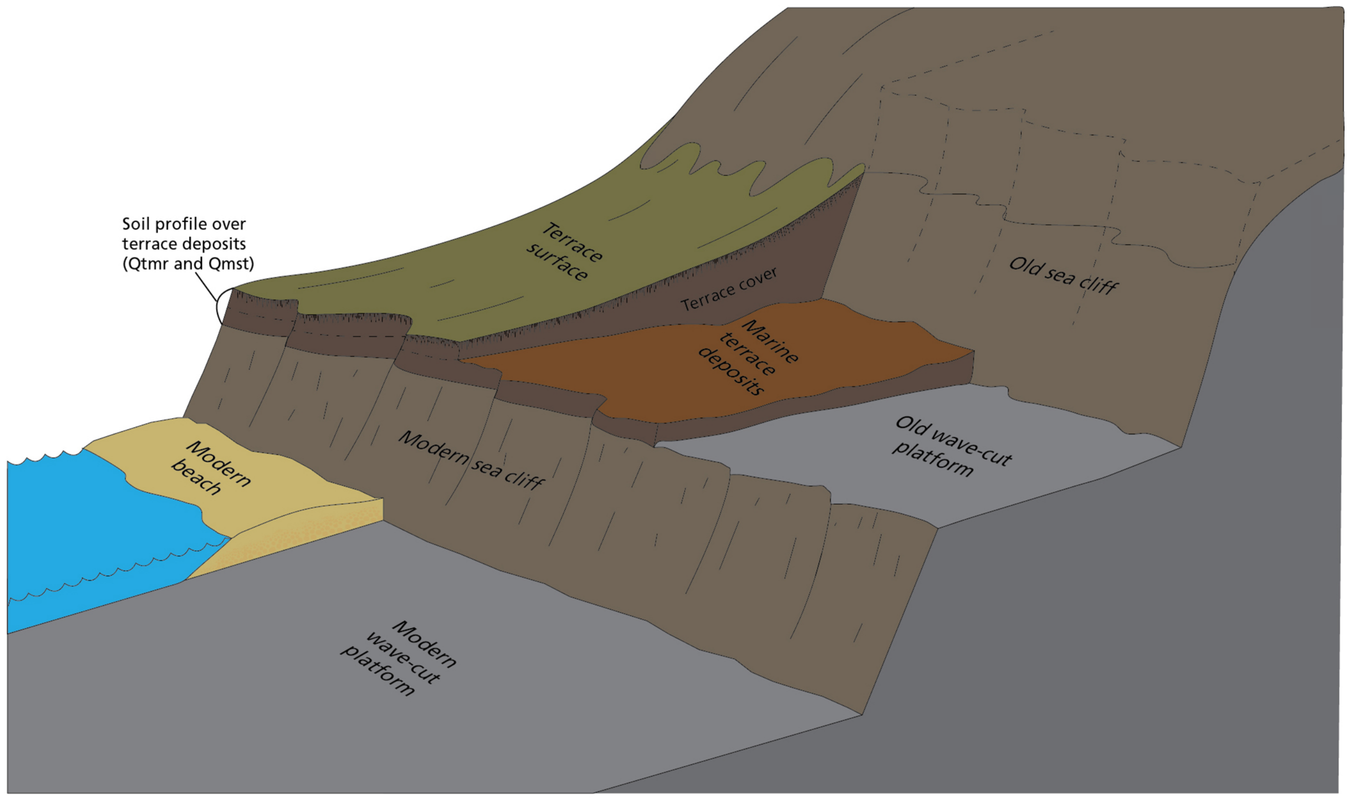


Figure 36. Illustration of a marine terrace and associated features.
The graphic illustrates the relationship of the wave-cut platform to the shoreline and overlying terrace deposits. Waves actively cut broad platforms into rocks exposed along the shoreline. If sea level drops or tectonic activity raises the land, the wave-cut platform becomes exposed above sea level forming a relatively flat, elevated area called a marine terrace. If uplift occurs repeatedly, several levels of marine terraces, each progressively older and higher, form landward of the shore. Graphic by Rebecca Port (NPS) redrafted from Weber and Allwardt (2001, figure 1.4, p.23).

Tomales Bay (inside cover) and Drakes Estero (fig. 34) are both drowned stream valleys; they are evidence of lower sea level during the last ice age. The valleys perpendicular to the coast between the Point Reyes Headlands and Drakes Beach are the remains of tributaries to a main stream which occupied Drakes Estero before it was flooded by the sea (Galloway 1977). The stream valleys probably originally formed during the most recent ice age (the "Wisconsin glaciation") and then became flooded by the roughly 120-m- (390-ft-) rise in sea level since the end of the last glacial maximum of the Quaternary Period, about 18,000 years ago (see "Geologic History" section; Galloway 1977; Stoffer 2006). At some point after the last ice age the sea invaded even farther than it extends today. The alluvium (**Qalo**) filling the lower reaches of the stream valleys which enter Drakes Estero (see poster in pocket) are an indication of how far the sea encroached and the cliff at the end of Drakes Head marks the extent to which the sea transgressed and cut the cliff back (Galloway 1977).

Ancient dune deposits (**Qobs**) also give an indication of how the coastline has changed over time. The sand in map unit **Qobs** at McClures Beach is fairly tightly cemented, but preserves bedding structures consistent with features of wind-blown sand deposits (fig. 21). These dunes probably formed in an ancient stream valley near the coast that today is being exhumed by modern McClures Creek (Stoffer 2006).

Waves

Waves continuously erode the coast and redistribute sediment. Active wave-cut platforms line the coast beneath many of the cliffs and bluffs in the park, many of which are only visible at low tide (figs. 19 and 35). For example, Palomarin Beach is underlain by a wave-cut platform comprised of Santa Cruz Mudstone (Tsc) which extends more than a half kilometer (half mile) into the ocean (fig. 35; Stoffer 2006; Cochrane et al. 2015). Year round, the park is subjected to moderate northwest wind-driven waves (wave heights of 1 to 4 m) with the addition of similarly sized local wind waves

from October to April (Storlazzi and Griggs, 2000; Storlazzi and Wingfield, 2005; Johnson et al. 2015). Large waves from the north Pacific swell (wave heights of 2 to 10 m) dominate in the winter months; smaller waves (wave heights of 0.3 to 3 m) generated by storms in the south Pacific are prominent in the summer (Storlazzi and Griggs, 2000; Storlazzi and Wingfield, 2005). Erosion and offshore transport of sediment is significant during large northwest winter swells (Johnson et al. 2015).

Coastal Erosion

The cliffs in the park are retreating at the fastest rate of any location in the northern San Francisco area. At Tomales Point, Hapke and Reid (2007) recorded 36.2 m (119 ft) of coastline retreat over the last 70 years with as much as 48 m (160 ft) of cliff retreat from 1929 to 2002. Between 1859 and 1977, Duxbury Point eroded about 60 m (200 ft) and Bolinas Point eroded about 50 m (160 ft) (Galloway 1977). The average rate of coastline and cliff retreat in the park is 0.5 m (1.6 ft) per year (fig. 37; Hapke and Reid 2007). Southern facing cliffs exhibit even higher retreat rates at 1.9 m (6.2 ft) per year (Hapke and Reid 2007). USGS measurements of coastal cliff retreat at Point Reyes for the time period from 1929–2010 showed that 83% of the park's coastal cliffs are retreating at rates between 0.1 and 1.0 m/yr (Patrick Limber, USGS, summary document provided by Ben Becker, Point Reyes National Seashore, science advisor, email, 1 November 2017). Refer to the "Coastal Resource Datasets" section in this report for more information on obtaining coastal erosion data. Most of the sea cliff retreat in the park occurs by landslides (see "Landslides" section).

Figure 37. Map of cliff erosion rates.
Historical cliff erosion is considered to be a crucial element in studying the vulnerability of the national coastline. The average rate of coastline and cliff retreat in the park is 0.5 m (1.6 ft) per year. The map above shows data by Hapke and Reid (2007) for Central California from 1929-2002. Map generated by the USGS Coastal Change Hazards Portal, available at https://marine.usgs.gov/coastalchangehazardsportal/.

The entire coastline of the park is not eroding. Point Reyes Beach (see fig. 1 for location), the longest beach in the park [19 km (12 mi)], has a long term history of accretion (growth) (fig. 38), though erosion has been recorded in the northernmost and southernmost reaches in the last 50 years (fig. 39; Hapke et al. 2006). Erosion rates in those areas varied from 0.1 to 0.7 m (0.3 to 2.3 ft) per year (Hapke et al. 2006). In just the last several years, rapid erosion removed many meters along South Beach and the former Ben Davis house (Ben Becker, Point Reyes National Seashore, science advisor, email, 10 September 2017).

Coastal Sediment Transport and Deposition

Coastal sediment is transported and deposited in the park primarily by waves, currents, and tides in the offshore, and by wind (eolian processes) and landslides onshore. Transportation and deposition by landslides is covered in the "Landslides" section.

Shallow sediment transport in the park is largely controlled by surface waves (Watt et al. 2015b). Littoral drift is the movement of beach sediment alongshore, or parallel to the coast, caused by waves approaching the coast at an oblique angle. In the park, littoral drift results from the dominant west-northwest swell direction and transports sand and coarse sediment derived mainly from ephemeral streams and local coastal erosion primarily to the south (Hapke et al. 2006; Patsch and Griggs 2007). Sediment supply into the park, however, is limited because Tomales Bay and Tomales Point trap sand brought by southward littoral drift (Johnson et al. 2015). The mouth of Tomales Bay is filled with sand displaying ripple marks. This trapping of sediment combined with limited sediment-storage space on the offshore shelf adjacent to Point Reyes Beach means the bedrock is covered by only a thin veneer [less than 2.5 m (8 ft)] of sediments (Watt et al. 2015b). Despite this, Point Reyes Beach has a history of accretion, the mechanisms of which are not fully understood (see previous section). Wave refraction around the Point Reyes Headlands creates a northward flowing longshore current within Drakes Bay (Stoffer 2006). This wave refraction helped erode the crescent shape into the bay and is responsible for building Limantour spit (Stoffer 2006). South of Limantour spit to Bolinas is another offshore shelf with only a thin veneer of sediment covering due to both limited supply and accommodation space (Watt et al. 2015b).

At depths greater than 20 to 30 m, sediment transport is controlled by tidal and subtidal currents; scour from large waves and strong tidal currents remove and redistribute sediment over large areas of the inner shelf (Watt et al. 2015b). Farther offshore, bottom currents generally flow to the northwest and distribute fine grained sediments typical of deeper water (Noble and Gelfenbaum 1990).

Eolian processes are primarily responsible for transportation and deposition of onshore sediment. Eolian processes refer to wind-blown erosion, transportation, and deposition of sediments (Lancaster 2009). In the park, wind transports sand and silt and deposits these sediments as dunes. The NPS Geologic Resources Division Eolian Resource Monitoring website, http://go.nps.gov/monitor_eolian, provides additional information. Both modern (**Qdsy**) and ancient (**Qobs**; see "Ancient Coastlines" section) dunes are included in the GRI GIS data. Point Reyes Beach is backed by dunes (see poster, in pocket). Where sea cliffs are low or nonexistent, like at Point Reyes Beach, wind blows sand inland to form dunes (Sloan 2006). The beaches at the park have both active (not stabilized) and inactive dunes. Some of the inactive dunes occur on ridge tops and are stabilized by vegetation, though they are not lithified (Sloan 2006, KellerLynn 2008). Dunes contain fossil pollen, which may be a source of paleoclimate data (see "Paleontological Resources" section; KellerLynn 2008).

Dunes are important in the park because they are part of the unimpaired state of the seashore, provide protection from coastal storms, and support at least 11 federally listed threatened or endangered species. Invasive species, organic enrichment, and manufactured structures such as landscaping and roads have impacted the natural condition of dunes in the park (see "Disturbed Lands Restoration" section; KellerLynn 2008).

Marine Resources

Marine resources—the Pacific Ocean, Drakes Bay, Tomales Bay, and Bolinas Bay and Lagoon—almost completely surround Point Reyes National Seashore and the boundary of the park extends 1 mile offshore (GRI conference call participants, 23 February 2016) so a brief mention of marine resources is included in this report. The Greater Farallones National Marine Sanctuary (administered by NOAA and designated in 1981; fig. 2) extends beyond the offshore boundary of the park.

Upwelling

Offshore from the park is the generally southward-flowing California Current, one of four major eastern boundary currents in the world and the eastern limb of the North Pacific Gyre (Hickey 1979). The California Current stretches along the western coast of North America from southern Canada to northern Mexico. Because the coast of California is along an active continental margin, ocean depth increases dramatically

Figure 38. Map of long term shoreline change rates.
The majority of the park's coastline has been relatively stable in the long term with change rates between -1 to 1 m per year (-3 to 3 ft per year). Point Reyes Beach has shown a long term history of accretion (growth). The map above shows data by Hapke et al. (2006) for Central California from 1853-2002. Map generated by the USGS Coastal Change Hazards Portal, available at https://marine.usgs.gov/coastalchangehazardsportal/.

relatively close to shore (see "Geologic Setting" section). Nutrients accumulate in deep, cold water. Wind-driven upwelling delivers a supply of nutrients from the deep to surface waters. These nutrients coupled with sunlight sustain microscopic sea plants. Tiny animals feed on them, and in turn become food for fish, seabirds, sharks and whales. The California Current ecosystem is one of the most biologically productive regions in the world (Office of National Marine Sanctuaries 2017).

Offshore Geology

USGS California Seafloor Mapping Program (CSMP) produced a 1:24,000-scale map series for the offshore areas surrounding Point Reyes National Seashore (see Cochrane et al. 2015; Johnson et al. 2015; Watt et al. 2015a; Watt et al. 2015b). The CSMP is a cooperative program to create a comprehensive coastal/marine geologic and habitat (bathymetry, marine benthic habitats, and geology) base map series for all of California's State waters (https://walrus.wr.usgs.gov/mapping/csmp/index.html). Maps cover the area within the 3-nautical-mile limit of California's State Waters. The map products display seafloor morphology and character, identify potential marine benthic habitats, and illustrate both the surficial seafloor geology and shallow [to about 100 m (330 ft)] subsurface geology. The GIS data for each map series can be downloaded from the publication's website. The data are not included in the GRI GIS data, however geologic information from these maps was considered during production of this report.

Because of Quaternary uplift which limits sediment accumulation space (see "Faults" section) and relative lack of sediment supply from coastal watersheds (see "Coastal Resources" section), the seafloor on the ocean side of Tomales Point and surrounding the Point Reyes

Figure 39. Map of short term shoreline change rates.
Shore term shoreline change rates reveal the north and south ends of Point Reyes Beach have been eroding recently (in the last 50 years), while the central area has remained stable or grown. The map above shows data by Hapke et al. (2006) for Central California from 1971-1998. Map generated by the USGS Coastal Change Hazards Portal, available at https://marine.usgs.gov/coastalchangehazardsportal/.

Headlands is rugged, rocky and primarily composed of massive and fractured Cretaceous granitic basement rocks (Johnson et al. 2015; Watt et al. 2015b). Sediment supply to the shelf along Point Reyes Beach is minimal because littoral drift is blocked to the north by Tomales Bay and Tomales Point, and to the south by the Point Reyes headland (Johnson et al. 2015). There is a distinct bathymetric gradient south of the Point Reyes Headlands related to the north-side-up motion on the Point Reyes Fault (Watt et al. 2015b). Water depth drops to about 150 feet within a few hundred feet of shore (Stoffer 2006). As a result, a large nearshore bar has formed around the headlands. The seafloor along Drakes Bay, north of Bolinas, is primarily Santa Cruz Mudstone, the Monterey Formation, or a combination of the Purisima Formation, Santa Cruz Mudstone, Monterey Formation mapped as late and middle Miocene, undivided sedimentary rocks (**Tu** on offshore maps) (Cochrane et al. 2015).

Paleontological Resources

Paleontological resources (fossils) are any evidence of life preserved in a geologic context (Santucci et al. 2009). All fossils are non-renewable. 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 June 2018, 268 parks, including Point Reyes National Seashore, had documented paleontological resources in at least one of these contexts. The NPS Fossils and Paleontology website, http://go.nps.gov/paleo, provides more information.

The park contains considerable paleontological resources (table 11) and the potential exists for

Table 11. Fossils documented in Point Reyes National Seashore

Note: List of fossils compiled using information from Elder et al. 2008; Galloway 1977; Clark and Brabb 1997.

Age of Map Unit from GRI GIS Data	Map Unit(s) (symbol)	Fossils
Pleistocene–Holocene	Unclear, possibly beach sand (Qbs), dune sand (Qdsy), or older beach sand (Qobs); samples collected via sediment cores at Coast Trail Pond, Sculptured Beach, and Secret Beach	Pollen (records transition from a closed canopy forest to a coastal scrub and grassland, suggesting the late Pleistocene climate was cooler and moister than today, Rypins et al. 1989)
late Pleistocene	Olema Creek Formation (Qoc)	Freshwater diatoms Tree trunks
late Pleistocene	Millerton Formation (Qml)	Crustaceans Mollusks (bivalves, gastropods, scaphopods [tusk shells]) Pine cones
Quaternary and late Pliocene	Merced Formation (QTm)	Bird feathers Sea lion, whale, porpoise Bony fish Sharks Crustaceans Mollusks Echinoderms Foraminifera, radiolarian, diatom molds Porifera (sponges) Wood and plant remains
Miocene–Pliocene	Purisima Formation (Tps) Santa Cruz Mudstone (Tsc) Santa Margarita Sandstone (Tsm)	Sea lion, seal, walrus skulls and ribs, vertebrae, bone material Dolphin and whale skulls, vertebrae, bone material Teleost fish Shark teeth Crustaceans (isopods, crab, shrimp) Mollusks Echinoderms Foraminifera, radiolarians, diatoms Wood and conifer cones
late and middle Miocene	Monterey Formation (Tm)	Cetaceans – fragments of whale bone and a cetacean skull Fish remains and scales Shrimp and crab Mollusks Echinoids Foraminifera and diatoms
middle Miocene	Laird Sandstone (Tls)	Mollusks – marine bivalves (including casts) Echinoids – group including sand dollars and sea urchins
early Eocene	Point Reyes Conglomerate of Galloway (1977) (Tpr)	Carbonized plant remains and seeds Foraminifera Small marine invertebrates

continued discovery (Elder et al. 2008). Paleontological resource inventory, monitoring, and protection is a resource management issue at the park as discussed in that section of this report. A park-specific paleontological resource inventory has not yet been completed; however, Elder et al. (2008) prepared a paleontological resource summary for the parks of the San Francisco Bay Area Network. They reported a diverse assemblage of marine fossils in the Cenozoic (Eocene-Pleistocene) sedimentary deposits within the park, including biostratigraphically important microfossils, invertebrates, and vertebrates. According to the park curator (K. Kvam, Point Reyes NS, Museum Curator, personal communication, 2007, cited in Elder et al. 2008) there are at least 15 paleontology specimens within park's collections.

Since the 2008 report, there has been significant research on the marine vertebrate fossil record (see Boessenecker 2011; Boessenecker and Perry 2011;

Boessenecker and Smith 2011; Boessenecker 2013a; Boessenecker 2013b) and marine mammals are now well known from within the park. The marine mammal record includes a new species of balaenopterid whale (figs. 40 and 41) (Elder et al. 2008). The Ken Patrick Visitor Center has a Pliocene baleen whale fossil (in addition to other marine fossils) on display. In 2017, nine crates of late Miocene marine mammal fossils were returned to the park after being illegally collected (see " Paleontolgical Resource Inventory, Monitoring, and Protection" section). The collection contained the skulls of several toothed whales (Odontoceti) including a specimen of beaked whale (family Ziphiidae), as well as a partial skull of an extremely rare and poorly understood dolphin (genus *Albireo*). There are less than half a dozen specimens of *Albireo* known worldwide. These specimens both likely represent new species of cetaceans (Vincent Santucci, NPS Geologic Resources Division, geologist, conference call, 17 August 2017).

Figure 40. Photograph of a fossil whale mandible from the Purisima Formation. The fossil was found on the western lobe of Drakes Head. NPS photograph by Lillian K. Pearson.

Figure 41. Photograph of a fossil whale bone.
This fossil was discovered in situ in the Purisima Formation along Drakes Beach. NPS photograph by Vincent L. Santucci.

Sea Caves

Caves are naturally occurring underground voids such as solutional caves (commonly associated with karst), lava tubes, sea caves, talus caves (a void among collapsed boulders), regolith caves (formed by soil piping), and glacier caves (ice-walled caves) (Toomey 2009). As of May 2017, cave or karst resources are documented in at least 159 parks, including Point Reyes National Seashore. 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. The exact number of caves in the park is not known (see "Sea Cave Inventory and Monitoring" section; Garrett and Williams 2008) although it is at least 139 according to a spreadsheet maintained by the NPS Cave and Karst Program. The caves are accessible by kayak, and some are accessible by land at low tide. Other types of caves may exist in the park, but none have been documented. Conditions in the park may allow for the formation of talus or regolith caves. 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 park.

Sea caves are a common feature in the cliffs up and down the coastline of California. Sea caves—clefts or cavities at the base of sea cliffs—form by erosion of cliff-forming rocks in high-energy tidal zones. 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. 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). Because these caves are at sea level, tides may affect them (KellerLynn 2008).

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, USGS, cave specialist, email, 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, sea stars, 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, 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, visual information specialist, conference call, 23 February 2016).

Geothermal Features and Processes

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 Point Reyes National Seashore. The NPS Geologic Resources Division Geothermal Systems Monitoring website, http://go.nps.gov/monitor_geothermal, provides additional information.

There is some evidence of geothermal activity in the park. Deep faults probably provide conduits for hydrothermal waters. For instance, the Palomarin area at the national seashore hosts sulfur seeps (KellerLynn 2008). Oil and gas seeps occur in the vicinity of Duxbury Point (Galloway 1977).

Geologic Resource Management

Some geologic features, processes, or human activities may require management for human safety, protection of infrastructure, and preservation of natural and cultural resources. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

Discussion of geologic resource management in this report is limited to the Point Reyes National Seashore authorized boundary. For information regarding the north district of Golden Gate National Recreation Area, refer to the GRI report for that park (Port 2016).

During the 2007 scoping meeting (see KellerLynn 2008) and 2016 conference call, and from a review of park documents, participants and the author (see Appendix A) identified the following resource management issues.

- Earthquake
- Landslides Hazards
- Flooding
- Coastal and Marine Resource Management and Planning
- Paleontological Resource Inventory, Monitoring, and Protection
- Sea Cave Inventory and Monitoring
- Disturbed Land Restoration
- Documentation and Reclamation of Abandoned Mineral Lands
- Conventional Energy and Mineral Extraction and Development
- Renewable Energy Development

The Geologic Resources Division provides technical and policy support for geologic resource management issues in three emphasis areas:

- geologic heritage,
- active processes and hazards, and
- energy and minerals management.

Contact the division (http://go.nps.gov/geology) for assistance with resource inventories, assessments and monitoring; impact mitigation, restoration, and adaptation; hazards risk management; law, policy, and guidance; resource management planning; data and information management; and outreach and youth programs (Geoscientists-in-the-Parks and Mosaics in Science). Park staff can formally request assistance via https://irma.nps.gov/Star/.

Resource managers may find *Geological Monitoring* (Young and Norby 2009; http://go.nps.gov/geomonitoring) useful for addressing geologic resource management issues. 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, suggested methods of monitoring, and case studies.

The Geoscientists-in-the-Park and Mosaics in Science programs are internship programs to place scientists (typically students and recent graduates) in parks to complete geoscience-related projects that may address resource management issues. Projects at Point Reyes National Seashore have included (as of March 2017):

- Interpretation and education projects in 2001 and 2002, and
- An inventory and monitoring project in 2016.

Projects are listed on the GIP website: http://go.nps.gov/gip_products. Products created by the program participants may be available on that website or by contacting the Geologic Resources Division. Refer to the programs' websites at http://go.nps.gov/gip and http://go.nps.gov/mosaics for more information.

Earthquakes

A serious earthquake will almost certainly 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"). According to a June 2016 USGS fact sheet, there is a 0.72 probability for such an earthquake somewhere in the San Francisco Bay Region before 2043 (Aagaard 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).

Currently seismic activity is "quiet" at the national seashore as the fault appears to be locked and "waiting" for the next large quake. The segments of the San Andreas Fault in the vicinity of the park have historically experienced earthquakes, rather than creep. 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.

The park has an emergency response plan in place (GRI conference call participants, 23 February 2016). Management concerns for the next large quake concentrate on roads. Disaster scenarios consider damage to the Golden Gate Bridge, which would affect emergency response to and evacuation of Point Reyes National Seashore and Golden Gate National Recreation Area.

Many organizations and resources are available to assist park staff with earthquake preparation and planning. The California Geological Survey (CGS) and cooperators study paleoseismology along the San Andreas Fault at a site just outside the boundaries of the national seashore (KellerLynn 2008). At this site, scientists have identified the slip rate and as many as 10 prehistoric quakes along the fault. Most of what is known about the San Andreas Fault has come from this site. Additionally many seismic stations are in the vicinity of Point Reyes National Seashore. Zones of required investigation for possible earthquake faulting, landslides, and liquefaction are delineated by the 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 promote preparedness and rapid recovery from the effects of earthquakes and natural hazards (see http://resilience.abag.ca.gov/). A series of interactive maps are available at: http://resilience.abag.ca.gov/earthquakes/.

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 USGS 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.

Earthquake Probability

Determining probability is the first step to assessing hazards. Currently, the USGS assesses earthquake potential with a model—the Uniform California Earthquake Rupture Forecast (UCERF). As of July 2017, 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 being prepared, the USGS released Fact Sheet 2016-3020: *Earthquake Outlook for the San Francisco Bay Region 2014–2043* (Aagaard 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. 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. It is mapped outside the park, but a strong earthquake on this 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 indeed all of the San Francisco Bay Area) has a high level of risk for earthquake shaking intensity and damage (fig. 42; Petersen et al. 2015; Branum et al. 2016). Both the USGS and California Geological Survey have projected intensity and likelihood of shaking in the area near the park. This information is periodically updated and available from their websites, https://earthquake.usgs.gov/hazards/hazmaps/ and http://www.conservation.ca.gov/cgs/rghm/psha/Pages/index.aspx, respectively.

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.

Creep also impacts infrastructure that crosses faults. For example, creep can eventually lead to surface rupture, offsetting and/or deforming curbs, streets, buildings, and other structures. Even if deformation occurs slowly, surface ruptures are a dramatic illustration of movement along a fault. The surface rupture in the park from the 1906 San Francisco Earthquake is one of the largest ruptures ever observed, though it is no longer apparent due to vegetation. Surface ruptures are the most easily avoided seismic hazard (USGS 2006). The primary strategy to reduce risk associated with creep and surface rupture is to avoid building infrastructure on top of 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. 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. Such materials perform poorly even under modest levels of shaking and can localize damage to specific areas (Lawson 1908).

The bulk of the peninsula has very low liquefaction potential, however, the few moderate to highly susceptible areas are near the Bear Valley Visitor Center and popular beaches (fig. 43; Knudsen et al. 2000). The most recent liquefaction susceptibility maps for the San Francisco Bay Area were published by the USGS and California Geological Survey in 2006 (Witter et al. 2006). Those maps did not cover north of San Francisco (e.g., Point Reyes National Seashore) or the Marin Headlands because updated mapping was still underway. Knudsen et al. (2000) provided regional scale mapping for the area including the park (fig. 43).

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 (USGS 2006).

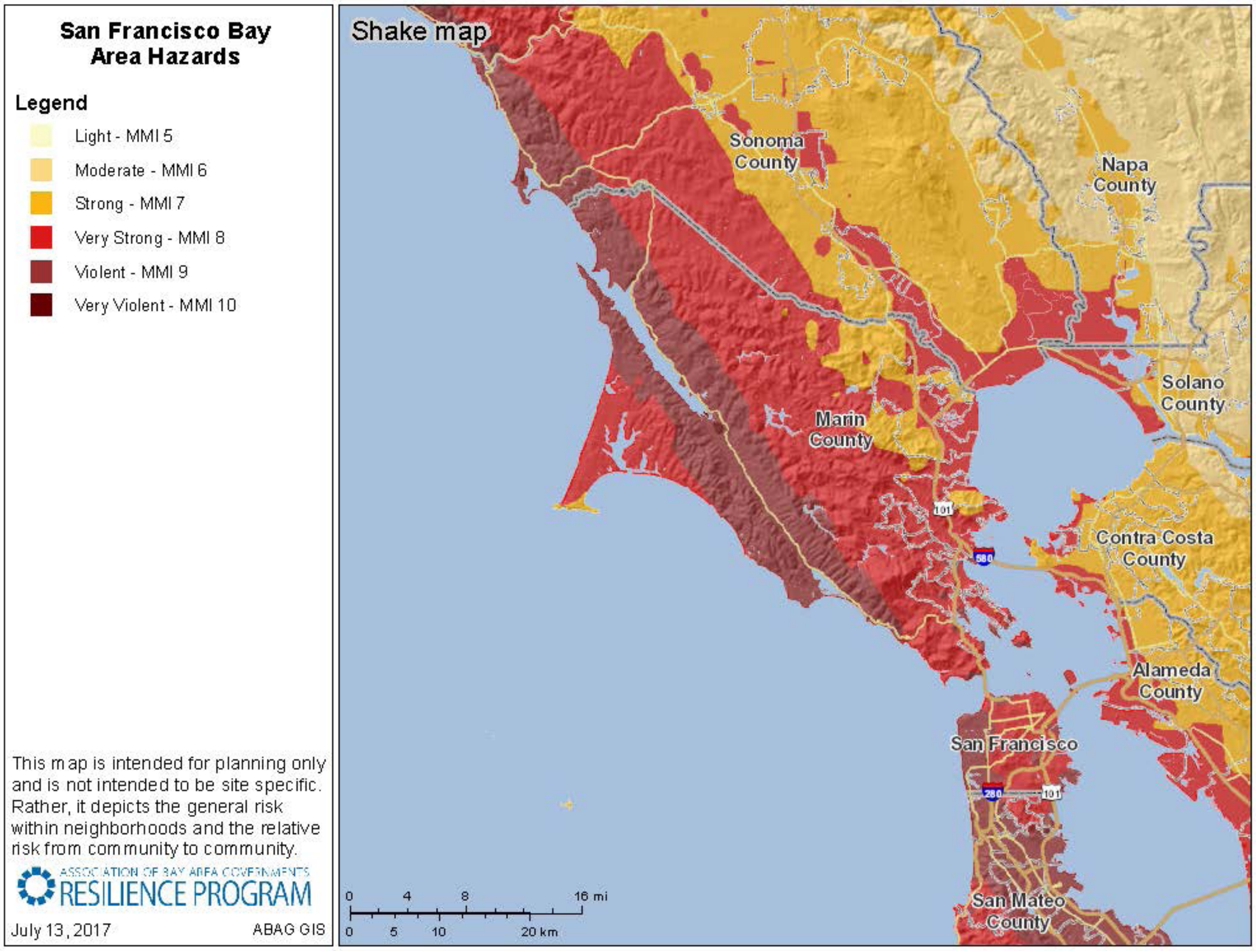


Figure 42. Map of earthquake shaking potential for the San Francisco Bay Area.
The map shows the expected severity of ground shaking and damage in the San Francisco Bay Area from a magnitude 7.8 earthquake on the San Andreas Fault. Intense shaking can damage even strong, modern buildings. Map generated by the Association of Bay Area Governments Resilience Program (http://resilience.abag.ca.gov/earthquakes/) using USGS data updated in 2012.

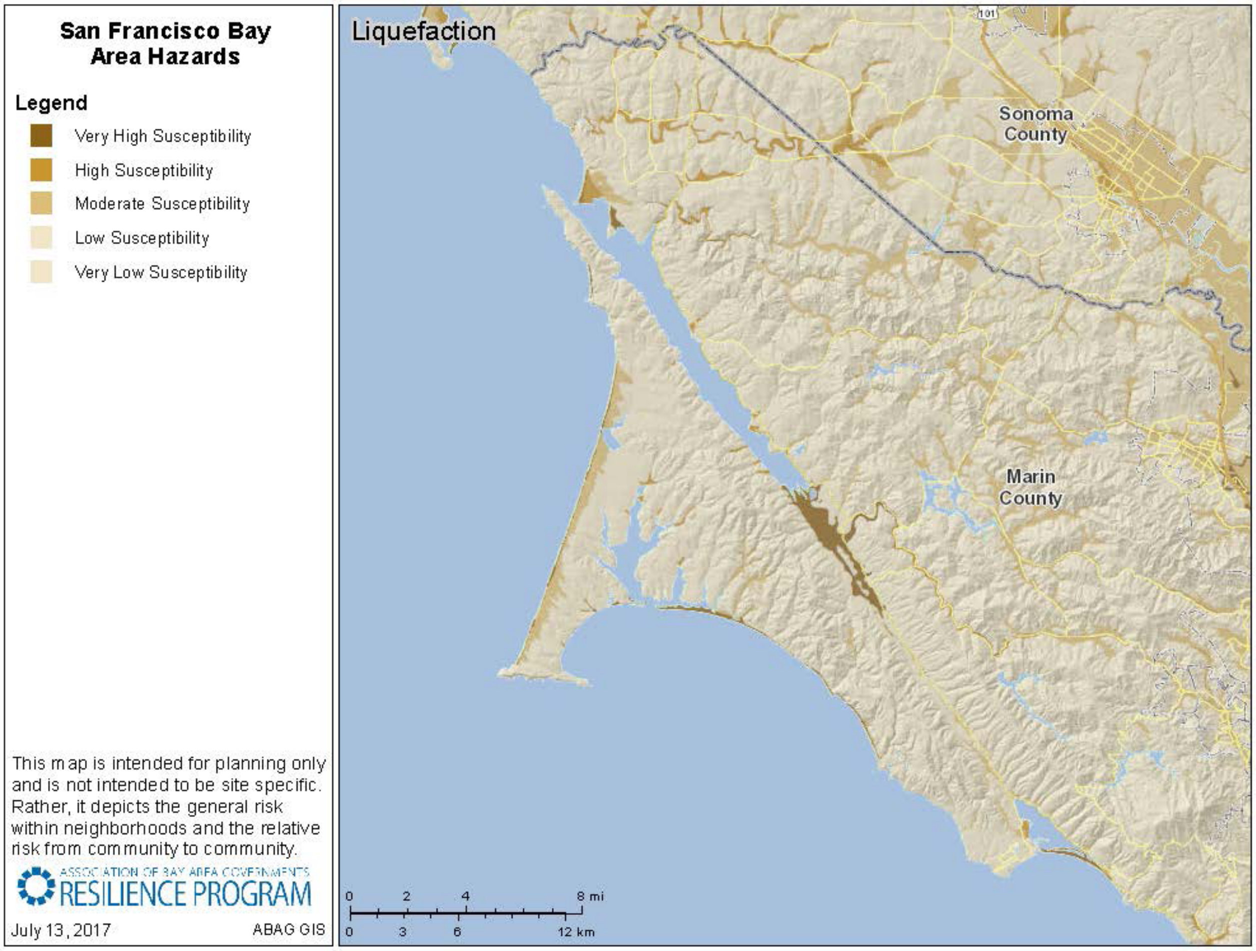


Figure 43. Liquefaction susceptibility map.
The bulk of the peninsula has a very low liquefaction potential. Point Reyes Beach, Limantour Spit, and Olema Valley are very highly susceptible to liquefaction during earthquakes. Dune sand and river valley sediments are moderate to highly susceptible. Map generated by the Association of Bay Area Governments Resilience Program (http://resilience.abag.ca.gov/earthquakes/) using data from Witter et al. (2006) and Knudsen et al. (2000).

Tsunamis

Earthquakes (triggered by fault movements) under the ocean may generate large waves called tsunamis. The park has been impacted by tsunamis in the past. Roger Byrne at the University of California–Berkeley determined that tsunami deposits in Bolinas Lagoon are on the scale of hundreds of years old (Byrne 2006). The 1906 earthquake is known to have generated a tsunami (Geist and Zoback 1999). Earthquakes generated hundreds or thousands of kilometers away could also produce tsunamis that may affect the park.

Local faults that could trigger tsunamis include the Point Reyes Fault, Rodgers Creek–Hayward Faults and San Gregorio Fault. If the Point Reyes Fault is active, it would have the largest potential for creating a tsunami near the park (see "Faults" section; Grove et al. 2010). The Point Reyes Fault is a reverse fault which means rocks on one side of the fault have moved up relative to rocks on the other side. Movement on this fault could cause a rapid displacement of water that creates a huge wave. The remaining faults in the area are strike-slip faults, meaning they slide past one another. Movement along these faults is less likely to disrupt the overlying water column significantly.

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://www.conservation.ca.gov/cgs/geologic_hazards/Tsunami/Inundation_Maps/Marin. 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/.

Landslide Hazards

Landslides are natural elements of landscape change. These natural processes become hazards when they have the potential to impact life and/or property. Landslides can damage infrastructure, clog drainage, and cause injuries and fatalities. High visitation beaches near the base of cliffs as well as trails across steep slopes and/or near cliffs are examples of places where there is a risk of losses due to 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 also Holmes et al. 2013). Alerting visitors to the hazards and risks associated with landslides, which the park already does through their website, social media, brochures, and signage, is a first step toward reducing the risk. Assessing risk involves identifying areas where there is a potential for loss (e.g. high-visitation beaches, locations of park infrastructure) and determining landslide susceptibility—likelihood of future landslides—in those areas.

Susceptibility

Susceptibility is greatest where: (1) landslides have already occurred, (2) in weak rocks, and/or (3) on steep slopes, though slides may occur on slopes graded as low as 15% if the conditions are right (Clague 1969, Wills et al. 2011). Steep slopes occur naturally along much of the coastline of the park, including the Point Reyes Headlands, Tomales Point, and around portions of Drakes Bay. Slope stability decreases further if bedding (rock layers) dips in the same direction as the land (fig. 44; Clague 1969). Steep slopes may also be "created" by human activities, such as road cutting. Other human activities, such as equipment loading, undercutting of slopes, vegetation removal, development, or activities that alters surface and subsurface drainage patterns can increase susceptibility (Spittler 2005; KellerLynn 2008). Weak rocks are produced by weathering, such as along the coast by wind and waves, and where rocks have been ground up or fractured by fault activity, such as near the active San Andreas Fault (Clague 1969; Bilderback 2015). Additionally, fires denude vegetation which can further destabilize slopes. Steep, recently burned areas are especially susceptible to a type of slope movement called a debris flow (fig. 31). Even modest rain storms during normal (non-El Niño) years can trigger post-wildfire debris flows. The USGS Post-Wildfire Landslide Hazards website, https://landslides.usgs.gov/research/wildfire/, has more information on how to assess this type of hazard.

Landslide Triggers

Typically an event will finally trigger movement in an area susceptible to landslides. Intense rainfall, earthquakes, and waves undercutting coastal cliffs are landslide triggers in the park (Wills et al. 2011). Climate change will likely result in an increase in severe storms and therefor an increase in rainfall triggered landslides (KellerLynn 2008).

Rainfall is the most frequent landslide trigger in the park. Shallow slumps and debris flows are most likely to occur in November and December when rainfall is enough to saturate the ground. This typically occurs when rain is falling in the range of tens of millimeters per hour (few to several inches per hour) with a total

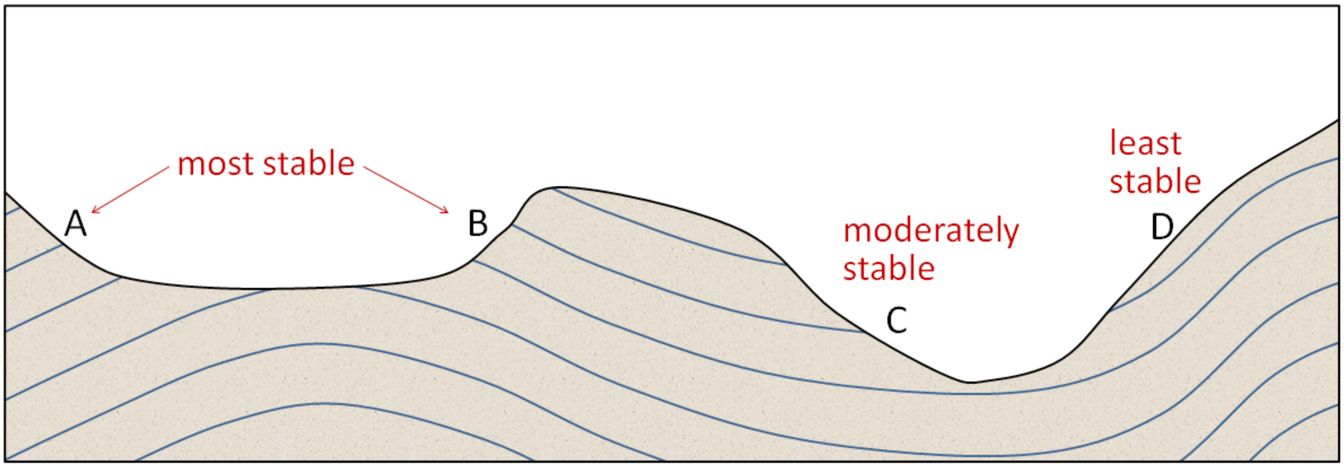


Figure 44. Illustration of slope stability scenarios.
Landslides commonly initiate along planes of weakness such as bedding planes (blue lines). Where the slope of the land and bedding planes are at nearly right angles, slopes are most stable (A and B above). Instability occurs where the slope of the land is roughly parallel to the bedding planes (C and D above); the more steep the incline, the more unstable the slope (D above). Graphic from Physical Geology by Steven Earle (figure 15.3) used under a CC-BY 4.0 international license, available at https://opentextbc.ca/geology/.

of at least 25 cm (10 in) (San Francisco Bay Landslide Mapping Team 1997). Deep-seated slumps tend to be triggered by prolonged intense rainfall towards the end of the winter season (March, April, May) (San Francisco Bay Landslide Mapping Team 1997). Prolonged rain is required for water to reach the bottom, "slip surface" of the landslide. During and just after storms, existing coastal landslides may become reactivated and seemingly stable coastal cliffs may erode and fail rapidly.

Guidance and Datasets

Managing landslide hazards involves (1) identifying landslide prone areas, so they may be avoided or the hazards mitigated, and (2) responding when landslides occur. Field observations, maps, and photographic monitoring can identify where landslides are likely to occur, though park managers should be aware that landslide locations can never be predicted with absolute certainty. Because past movements are a good first order indication of future slides, evidence of past landslide activity as well as evidence of active instability should be documented during field observations. The following recognizable features or occurrences in the park are a good indication of potential future landslides (Galloway 1977; USGS landslide preparedness website https://landslides.usgs.gov/learn/prepare.php):

- Steep slopes or cliffs composed of weak and/or crumbling rocks.
- Fissures in the ground and new cracks or unusual bulges in the ground, street pavements or sidewalks (fig. 32).
- Closed depressions (fig. 33).
- Rotated bedding (fig. 18).
- Disrupted strata.
- Planes of sliding.
- Bedding planes dipping steeply in the same direction as the slope of the land (fig. 44).
- Springs, seeps, or saturated ground in areas that have not typically been wet before.
- Soil moving away from foundations.
- Sunken or down-dropped road beds.
- Rapid increase in creek water levels, possibly accompanied by increased turbidity (soil content).
- Sudden decrease in creek water levels though rain is still falling or just recently stopped.
- Sticking doors and windows, and visible open spaces indicating jambs and frames out of plumb.

Landslide maps can be compiled to determine landslide prone areas over a larger area than possible with field observations. At its most basic a landslide map is an inventory, displaying the locations of prior and therefore probable future failure. Areas of historic coastal cliff retreat would also indicate places most susceptible to coastal landslides (see "Coastal Resource Datasets" section and Hapke and Reid 2007). A landslide-susceptibility map describes the relative likelihood of future landslides by rock or soil strength

and steepness of slope in addition to prior failure. Landslide-potential maps supplement susceptibility maps by factoring in an estimate or measure of the probability (likelihood of occurrence) of a triggering event such as earthquake or excessive rainfall. Landslide-risk maps describe landslide potential jointly with the expected losses to life and property if a failure was to occur. Landslide-zone maps depict areas with a higher probability of landsliding, within which specific actions are mandated by California law prior to any development. Available maps which cover the area of the park are described below. A specialist should be consulted to determine if these maps are suitable for determining landslide susceptibility in the park or if more information is needed; the GRD can assist with this determination.

The California Geological Survey produces these types of maps and may also be able to assist the park; information is available at http://www.conservation.ca.gov/cgs/geologic_hazards/landslides/Pages/Index.aspx. The Survey's Landslide Inventory and Deep Landslide Susceptibility Map (fig. 45; http://maps.conservation.ca.gov/cgs/lsi/) shows mapped landslide deposits and areas of weak rocks and/or steep slopes leading to susceptibility to deep landslides as determined by Wills et al. (2011). The landslides deposits shown on this viewer within the park are all classified as "CGS Mapped, Needs Review Single Feature, Deposit, and Source Features". The original maps and reports that the deposits are based on can be located through the viewer (mainly Wagner 1977). Landslide deposits in the park on this web map occur in southern Point Reyes near Bolinas and along the east side of Inverness Ridge. The absence of mapped landslides does not indicate that landslides are not present or that the area is less susceptible to landslides.

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 also based on work by Wills et al. (2011).

The USGS published a reconnaissance landslide map of part of Marin County in 1975 (Wentworth and Frizzell 1975). In 1997, the San Francisco Bay Landslide Mapping Team of the USGS produced maps of debris flow source areas and deep-seated landslides in Marin County, and developed a simple way to determine the locations of landslides by referencing published topographic quadrangle maps (1997). Since then, the USGS has mapped coastal landslides and cliff erosion rates in order to identify landslide/erosion hazard areas (e.g. Arch Rock) and to understand recent patterns of coastal change around the park (Patrick Limber, USGS, geologist, email, 19 February 2016). The USGS has not yet published their findings at the time of this report, but did deliver a summary report and GIS data directly to staff at Point Reyes National Seashore. The summary report indicated 83% of the Point Reyes coastline is in a "medium" or "high" hazard zone, and zones of "extreme" hazard exist in the southern part of the park, towards Bolinas, where large landslides occur within the Santa Cruz Mudstone and Monterey Formation (Patrick Limber, USGS, summary document provided by Ben Becker, Point Reyes National Seashore, science advisor, email, 1 November 2017).

Photographic techniques support structural analysis of the stability of rockfall areas. Following the 2015 collapse at Arch Rock, the USGS recommended photographic monitoring of the remaining promontory to quantitatively detect change in the portion of the promontory that can be safely photographed (Bilderback 2015). The Geoscientist-in-the-Parks program is an option to support such a project. The NPS Geologic Resources Division Photogrammetry website (http://go.nps.gov/grd_photogrammetry) provides examples of photographic techniques used in parks. These techniques could be employed to assess other rockfall areas in the park as well.

Once landslide prone areas have been identified, the hazard can be reduced by restricting access to and not building on or around the susceptible area. Hazard mitigation strategies include planting ground cover, building retaining walls, and communicating the risks to park visitors. During and following a landslide, certain measures should be taken to minimize further risk. According to the USGS landslide preparedness website (https://landslides.usgs.gov/learn/prepare.php):

- Stay away from the slide area. There may be danger of additional slides.
- Watch for flooding, which may occur after a landslide or debris flow.
- Listen for any unusual sounds that might indicate moving debris, such as trees cracking or boulders knocking together.
- Look for sudden increase or decrease in water flow and for a change from clear to muddy water.
- Do not cross flooding streams.
- Be aware that strong shaking from earthquakes can induce or intensify the effects of landslides.
- Look for and report broken utility lines and damaged roadways and trails.
- Check building foundations, chimneys, and surrounding land for damage.

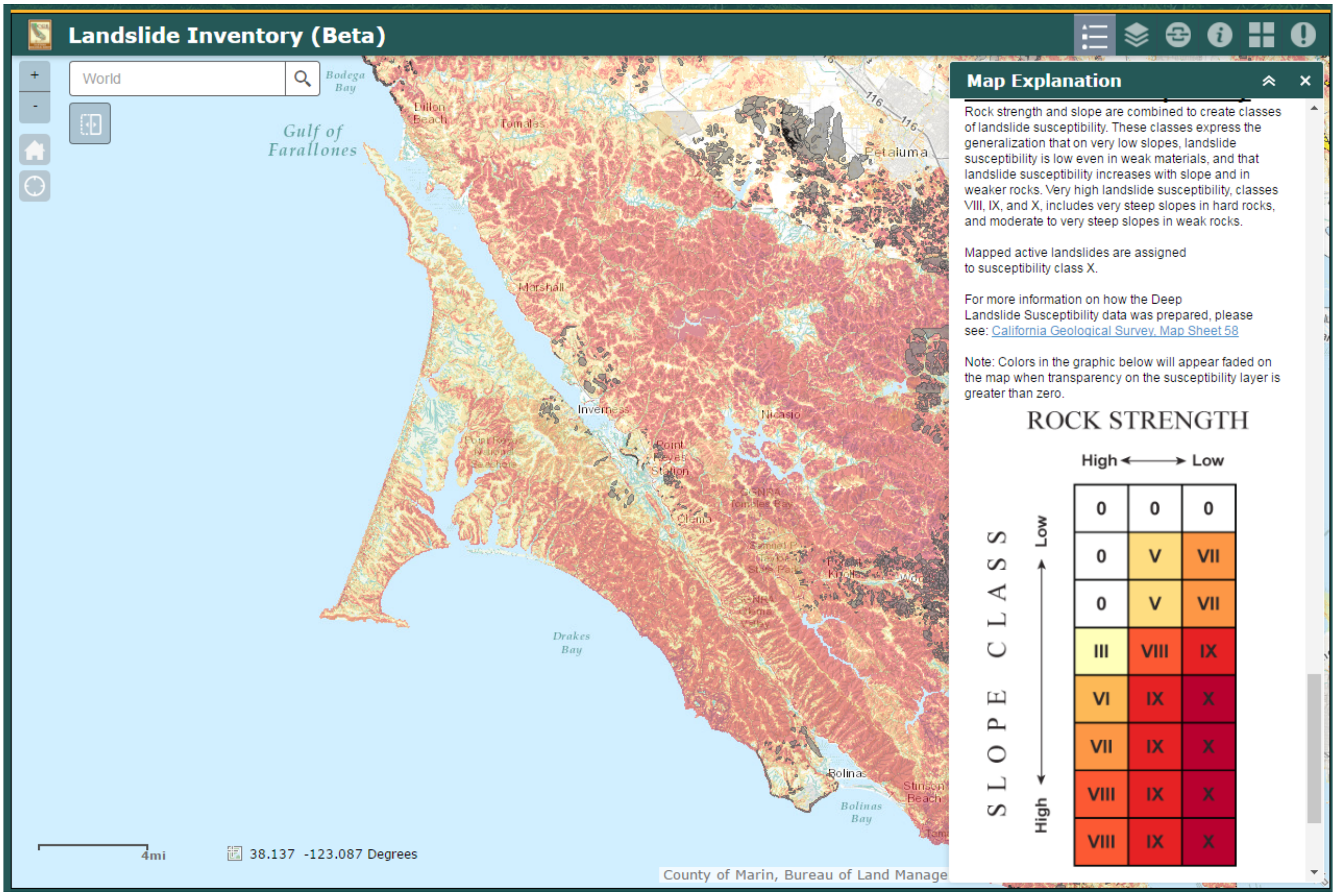


Figure 45. Map of landslide susceptibility.
Rock strength and slope were combined to create classes of landslide susceptibility. Landslide susceptibility is greatest in the southern region of the park where the steep slopes of Inverness Ridge combine with the relatively weaker Tertiary marine rocks (weaker than Cretaceous granitic rocks which are mapped on the north half of Inverness Ridge). Graphic created using data from Wills et al. (2011) by the California Geological Survey Landslide Inventory viewer, available at http://maps.conservation.ca.gov/cgs/lsi/.

- If appropriate, replant damaged ground as soon as possible since erosion caused by loss of ground cover can lead to flash flooding and additional landslides in the near future.

In addition to the websites and reports discussed above that can provide park-specific information, the following references provide further background information, suggested vital signs, and resources for assessing and documenting slope movements:

- In the *Geological Monitoring* chapter about slope movements, Wieczorek and Snyder (2009) described five vital signs for understanding and monitoring 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 (http://go.nps.gov/monitor_slopes).
- US Geologic Survey publication *The landslide handbook—A guide to understanding landslides* (Highland and Bobrowsky 2008; http://pubs.usgs.gov/circ/1325/).
- US Geological Survey landslides website (http://landslides.usgs.gov/).
- NPS Geologic Resources Division Geohazards website (http://go.nps.gov/geohazards).
- NPS Geologic Resources Division Slope Movement Monitoring website (http://go.nps.gov/monitor_slopes).

Flooding

Flooding caused by storms, El Niño events, and King Tides (an especially high-tide event occurring several times per year) can inundate roads, trails, and beaches, as it did in January 2017 when this report was being prepared. Steep basins and shallow soils promote rapid runoff and "flashy" storm flow

(KellerLynn 2008). Maximum flows and runoff occurs during and immediately after winter storms (fig. 46); flooding is less common in the summer months. In places, infrastructure exacerbates flooding damage, for instance at poorly engineered culverts and where channels are armored; it also impedes natural streamflow. Much of the infrastructure in the floodplains (e.g., pre-1960s stream crossings, dams, and roads) is in poor condition. Past land-use practices dramatically changed flooding conditions and floodplain morphology. Changes in natural flooding regimes are resulting in the invasion of exotic species in riparian areas.

Coastal flooding is a concern because the shoreline is a popular destination for park visitors. Climate change-related sea level rise also contributes to coastal flooding. Refer to the "Sea Level Rise" section for more information. Where flooding occurs downstream (and outside) of park lands, land owners want the National Park Service to "take action." 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).

The USGS Coastal Storm Modeling System (CoSMoS; https://walrus.wr.usgs.gov/coastal_processes/cosmos/) predicts coastal flooding due to both future sea level rise and storms. CoSMoS models are designed for use in community-level coastal planning and decision-making. CoSMoS produced a suite of coastal flooding projections for over 40 combinations of anticipated sea level rise and storm conditions from Bodega Bay south to Half Moon Bay. Results can be accessed, viewed, and downloaded through the Our Coast, Our Future flood mapper (http://data.pointblue.org/apps/ocof/cms/).

Coastal and Marine Resource Management and Planning

The NPS has developed a variety of databases 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 California Coastal Commission (https://www.coastal.ca.gov/) and California Coastal Conservancy (http://scc.ca.gov/) are responsible for administering the California Coastal Management Program. Point Reyes National Seashore can work with these agencies on issues related to their shoreline.

The Coastal Adaptation Strategies Handbook (Beavers et al. 2016; https://www.nps.gov/subjects/climatechange/coastalhandbook.htm) summarizes the current state of NPS climate adaptation and key approaches currently in practice or considered for climate change adaptation in coastal areas in order to guide adaptation planning in coastal parks. The chapters focus on policy, planning, cultural resources, natural resources, facility management, and communication/education. The handbook highlights processes, tools and examples that are applicable to many types of NPS plans and decisions.

The Cultural Resources Climate Change Strategy (Rockman et al. 2016; https://www.nps.gov/subjects/climatechange/culturalresourcesstrategy.htm) can assist with managing impacts to cultural resources from climate change. A vulnerability assessment for coastal archeological sites and traditional cultural properties at Point Reyes National Seashore (Newland 2013) provides detailed analyses of climate impacts across different ecosystems within a single park, such as ocean acidification effects on cliff areas, sea level rise in tidal marshes, and wildfire along cliff tops. This report also provides a list of questions developed by the culturally associated tribe (the Federated Indians of Graton Rancheria) to help guide development of policies to manage archeological and ethnographic resources that may be increasingly exposed to weathering and unauthorized collection when exposed by storms and erosion (Schupp et al. 2016).

Additional Reference Manuals that guide coastal resource management include *NPS Reference Manual #39-1: Ocean and Coastal Park Jurisdiction*, which can provide insight for parks with boundaries that may shift with changing shorelines (available at http://www.nps.gov/applications/npspolicy/DOrders.cfm); and *NPS Reference Manual #39-2: Beach Nourishment Guidance* (Dallas et al. 2012) for planning and managing nourishment projects. In the *Geological Monitoring* chapter about coastal features and processes 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. In the chapter about marine features and processes, Bush (2009) described five methods and vital signs for monitoring marine features and processes: (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.

Figure 46. Photograph of a flooded park road.
A stream flooded the roadway following heavy rain in January 2017. Maximum annual stream flow typically occurs during and immediately after winter storms. NPS photograph.

Coastal Resource Datasets

Pendleton et al. (2005) completed a coastal vulnerability index (CVI) assessment for Point Reyes National Seashore (fig. 47). 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. The CVI provides data for resource management and park facilities plans. For more information about CVIs, refer to the USGS CVI website: http://woodshole.er.usgs.gov/project-pages/nps-cvi/. Of the 50 miles of coastline, 24% of the coastline has a very high vulnerability ranking, 26% has a high vulnerability ranking, 26% has a moderate vulnerability and 24% has a low vulnerability ranking (Pendleton et al. 2005).

The Pacific Coastal and Marine Service Center (PCMSC) of the USGS is developing a risk model of shoreline collapse for the Point Reyes Coastline. They will use inputs from recent LiDAR data, erosion, and wave action to deliver a risk map of the park. Their first site visit occurred in October 2015. More information about the PCMSC is available at https://walrus.wr.usgs.gov/index.html.

USGS California Seafloor Mapping Program (CSMP) has produced a 1:24,000-scale map series for the offshore areas surrounding Point Reyes National Seashore (see Cochrane et al. 2015; Johnson et al. 2015; Watt et al. 2015a; Watt et al. 2015b). These maps could be converted into the GRI GIS data model and be used seamlessly with GRI GIS data; a potentially valuable expansion of the GRI GIS data for resource management. The park may consider requesting this as part of an "inventories 2.0" project.

A GIS compilation of vector datasets for shoreline change and cliff retreat in the park are available through the USGS (Hakpe et al. 2006; Hapke and Reid 2007). All of the files necessary to run shoreline change analysis and to conduct coastal cliff retreat analyses are provided. The Digital Shoreline Analysis System (DSAS) was used for the analysis of this data. DSAS is computer software that computes rate-of-change statistics from multiple historic shoreline positions residing in a GIS. It is also useful for computing rates of change for just about any other boundary change problem that incorporates a clearly-identified feature position at discrete times. The DSAS software is freely available (https://woodshole.er.usgs.gov/project-pages/DSAS/; Thieler et al. 2017).

Cliff retreat was determined by comparing the positions of one historical cliff edge digitized from maps with a modern cliff edge derived from topographic LiDAR surveys (fig. 37). Historical cliff edges for the California coast represent the 1920s-1930s time-period; the recent cliff edge was delineated using data collected between 1998 and 2002. End-point rate calculations were used to evaluate rates of erosion between the two cliff edges. Refer to the "Coastal Erosion" section of this report and the Hapke and Reid (2007) report on cliff edge erosion along the California coastline for additional information regarding methods and results.

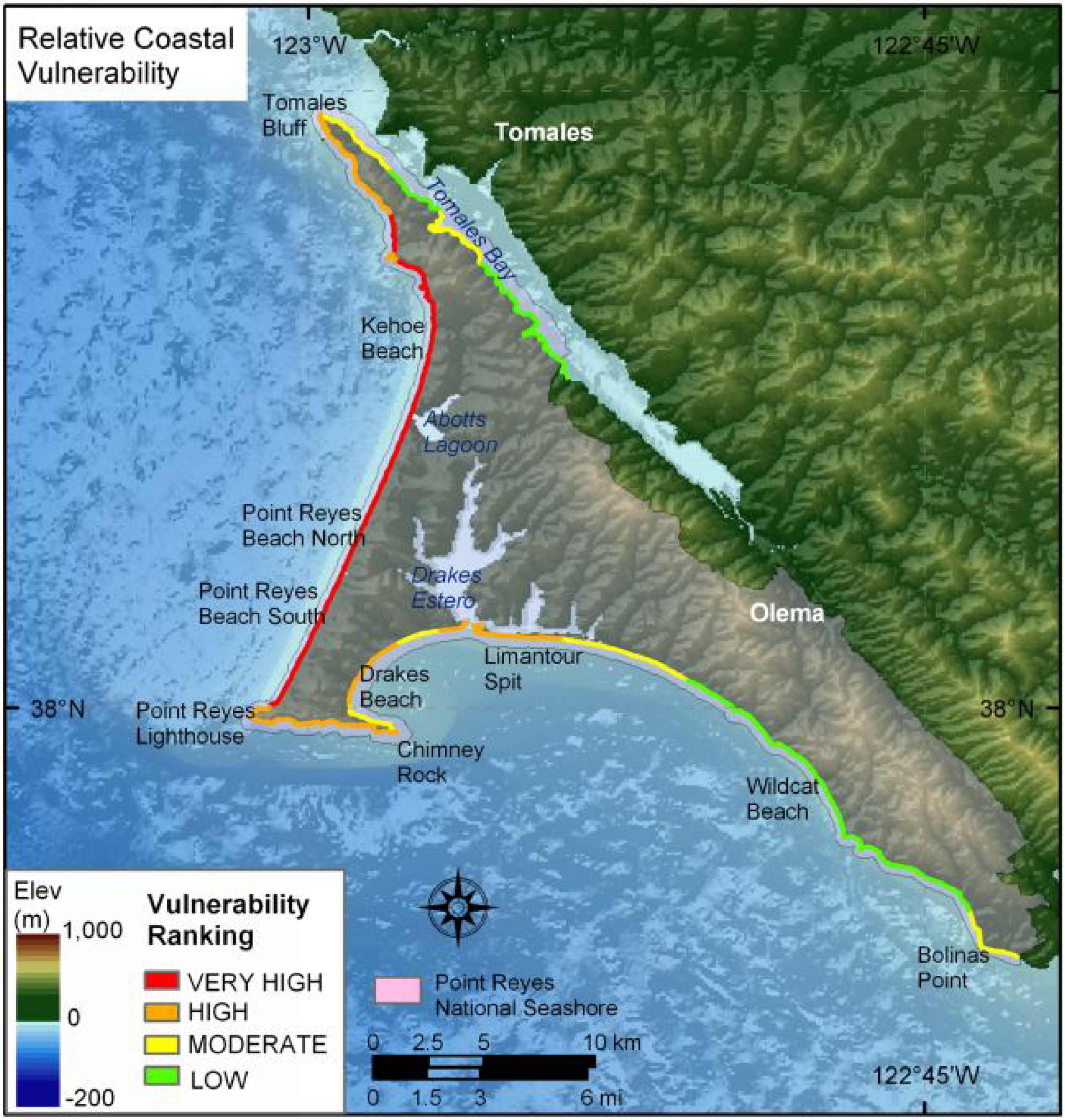


Figure 47. Relative coastal vulnerability map of Point Reyes National Seashore. The very high vulnerability shoreline is along sandy beaches where significant wave heights are highest and regional coastal slope vulnerability is low. The lower vulnerability shoreline is along rock cliffs where wave heights are lower and coastal slope is steep. USGS graphic by Pendleton et al. (2005, figure 11).

The USGS has mapped coastal landslides and cliff erosion rates in order to identify landslide/erosion hazard areas (e.g. Arch Rock) and to understand recent patterns of coastal change around the park (see "Landslide Hazards" section; Patrick Limber, USGS, email, 19 February 2016). The USGS has not yet published their findings at the time of this report, but did deliver a summary report and GIS data directly to staff at Point Reyes National Seashore. The summary report indicated 83% of the Point Reyes coastline is

in a “medium” or “high” hazard zone, and zones of “extreme” hazard exist in the southern part of the park (Patrick Limber, USGS, summary document provided by Ben Becker, Point Reyes National Seashore, science advisor, email, 1 November 2017).

Short term and long term shoreline change evaluations were determined by comparing the positions of three historical shorelines digitized from maps, with a modern shoreline derived from LiDAR (light detection and ranging) topographic surveys (figs. 38 and 39). Historical shorelines generally represent the following time-periods: 1850s-1880s, 1920s-1930s, and late 1940s-1970s. The most recent shoreline is from data collected between 1997 and 2002. Long-term rates of change are calculated by linear regression using all four shorelines. Short-term rates of change are end-point rate calculations using the two most recent shorelines. Refer to the “Coastal Erosion” section of this report and the Hapke et al. (2006) report on shoreline change of the California coastline for additional information regarding methods and results.

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. 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. Current patterns in climate change will accelerate sea level rise.

Since the 1950s, sea level rise has accelerated. 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). Satellite altimetry data shows that present-day global relative sea levels are increasing at approximately 3.3 mm/yr (0.13 in/yr) (Fasullo et al. 2016; Cazenave et al. 2014). Since 1970, the primary driver of increasing global sea level rise has been melting of polar ice caused by the release of anthropogenic greenhouse gases (Slangan et al. 2016). Sea level has risen about 125 to 130 m over about the last 21,000 years since the last glacial maximum (ice age; see Lambeck and Chappell, 2001; Peltier and Fairbanks 2006), leading to broadening of the continental shelf, progressive eastward migration of the California shoreline and wave-cut platform, and associated transgressive erosion and deposition (Johnson et al. 2015).

The rate of global sea level rise is very likely to increase (IPCC 2013). Sea level rise models and scenarios predict that global average sea level will rise by at least 0.3 m (1 ft) and up to as much as 1.2 m (4 ft) by the end of this century (The World Bank 2012; Church et al. 2013; US Army Corps of Engineers 2013; Melillo et al. 2014). 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 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 (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. Higher sea levels worsen the impacts of storm surge, high tides, and wave action (Sweet et al. 2017).Flooding associated with King Tides gives resources managers a glimpse of what permanent sea level rise could look like in the park (fig. 48).

Park facilities will also 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), 639 coastal assets are mapped within Point Reyes National Seashore and 25 of them (4%) are considered “high exposure” to 1 m (3 ft) of sea level rise.

Figure 48. Photographs of the potential impacts of sea level rise on Schooner Creek.
Top photograph is a King Tide and bottom photograph, taken 6 hours later, is a negative tide. The King Tide shows what could be the new normal with sea level rise. NPS photographs.

Changing relative sea levels and the potential for increasing storm surges due to anthropogenic climate change present challenges to national park managers. The NPS Geologic Resources Division and Climate Change Response developed sea level rise and storm surge data that parks can use for planning purposes over multiple time horizons (Caffrey et al. 2018). The project, led by Maria Caffrey of NPS Geologic Resources Division, analyzed rates of sea level coupled with potential storm surge in 118 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 (table 12). The report used information from the United Nations Intergovernmental Panel on Climate Change (IPCC) and storm surge scenarios from National Oceanic and Atmospheric Administration (NOAA) models. This research was the first to analyze IPCC and NOAA projections of sea level and storm surge under climate change for U.S. national parks. Results illustrate potential future inundation and storm surge due to climate change under four greenhouse gas emissions scenarios. Based on work by Caffrey et al. (2018) sea level is projected to rise by a minimum of 0.1 m by 2030 to at least 0.55 m by 2100at Point Reyes National Seashore (table 12).

Planning for Sea Level Rise

Accurate information regarding sea level rise is needed for many park management plans, project plans, and coastal adaptation strategies. 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 (fig. 47; see the "Coastal Resource Datasets" 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 (table 12; Caffrey et al. 2018).

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). Two coastal adaptation strategies for historical infrastructure such as forts and lighthouses are *retreat* and *fortify in place*; these are described by Caffrey and Beavers (2008). Additional strategies are presented in the Coastal Adaptation Strategies Handbook (Beavers et al. 2016; https://www.nps.gov/subjects/climatechange/coastalhandbook.htm). In many cases, the *fortify in place* strategy involves adding a seawall or other structure which can damage or destroy the natural environment. Therefore, adaptation strategies take into account both FMSS-listed park assets and other NPS resources (Peek et al. 2015). Cultural resources are also addressed in the Cultural Resources Climate Change Strategy (Rockman et al. 2016; https://www.nps.gov/subjects/climatechange/culturalresourcesstrategy.htm).

Tools that may be useful for determining sea level rise impacts include NOAA's hosted digital Sea Level Rise and Coastal Flooding Impacts viewer (http://coast.noaa.gov/slr/), the Coastal One-Line Assimilated Simulation Tool (see "Flooding" section; https://walrus.wr.usgs.gov/coastal_processes/cosmos/), and the US Army Corps of Engineer's Sea Level Change Calculator, which can be used with input from the Point Reyes tide gauge 9415020 (http://corpsclimate.us/ccaceslcurves.cfm). In addition, park managers may benefit from consulting with local agencies, such as the Association of Bay Area Governments Resilience Program and the Bay Conservation Development Commission Adapting to Rising Tides Program, which are partnering to create a process that will support the development of climate adaptation plans.

Table 12. Sea level rise projections in meters for Point Reyes National Seashore.

Note: Data from Caffrey et al. (2018).

*Representative Concentration Pathways are climate change scenarios based on potential greenhouse gas concentration (not emissions) trajectories introduced in the fifth climate change assessment report of the IPCC (2013).

Representative Concentration Pathways*	2.6	4.4	6.0	8.5
By the year 2030	0.11 m	0.1 m	0.1 m	0.1 m
By the year 2050	0.19 m	0.19 m	0.18 m	0.19 m
By the year 2100	0.38 m	0.43 m	0.45 m	0.55 m

Paleontological Resource Inventory, Monitoring, and Protection

Fossils within the park are significant and summarized in reports by Galloway (1977), Elder et al. (2008), and the "Paleontological Resources" section of this report. Several of the fossil sites in the park are in high-visitation areas where fossils can easily be disturbed and/or are locally known to produce fossils (e.g. Bolinas Point, Drakes Beach, and Kehoe Beach) (Pearson et al. 2016). Coastal erosion exposes fossiliferous rocks and threatens the long-term stability and condition of fossils (Pearson et al. 2016). Fractures, faulting and folding that occur in the rocks of Point Reyes are in proximity to the active San Andreas Fault system and result in frequent rockfalls, bluff collapses and landslides which may also contribute to the loss of or damage to paleontological resources (see "Landslide Hazards" section; Bilderback 2015; Pearson et al. 2016). 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).

All paleontological resources are non-renewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act (see Appendix B). As of Summer 2018, 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 aforementioned reports, a variety of publications and resources provide 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.

With increasing visitation, there is increased potential for illegal (unpermitted) fossil collecting within the park. As with all National Park Service areas, fossil collecting is prohibited. However, this regulation may not be common knowledge for all visitors. In 2017, a complex recovery operation culminated in the return of nine crates of fossils that were illegally collected in the park more than a decade ago (Vincent Santucci, NPS Geologic Resources Division, geologist, conference call, 17 August 2017). The recovered specimens included significant late Miocene marine mammals and one extremely rare species (see "Paleontological Resources" section). This recovery operation could serve as a model for future recovery efforts at Point Reyes and other NPS units. 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.

Pearson et al. (2016) developed protocols for monitoring paleontological resource sites at Point Reyes National Seashore. Monitoring using a protocol is important because it will supply scientifically-derived information on the rate and degree of impacts on resources and may provide the basis for future administrative actions involving their management. The protocol also analyzes how climate change may affect paleontological resources. The protocol offers monitoring methods and strategies for mitigation in areas that are or will become vulnerable therefore avoiding further degradation and potential loss of fossils. It provides a standardized method for managing fossil resources subject to the "no impairment" standard set forth in the National Park Service Organic Act. It also fulfills mandates in the Paleontological Resources Preservation Act (2009) that paleontological resources on Federal land be managed and protected using scientific principles and expertise. The report provides reporting and monitoring forms as well as guidelines for fieldwork and office procedures.

Elder et al. (2008) made the following paleontological resource management preliminary recommendations:

- Given the diversity of fossil resources known from the park and the potential for continued fossil discovery, a field-based inventory of paleontological resources from the park is recommended.
- The field work could be accomplished by establishing a cooperative agreement with one or more of the dominant natural history museums, universities, or USGS. The NPS Geologic Resources Division can help advertise, recruit, and provide technical assistance for these efforts.
- Results of the field inventory can be used to create paleontological resource monitoring prescriptions, should the park establish a program of paleontological resource monitoring.
- Interviews with the dominant specialists within each discipline that have worked in the park would provide considerable background. These interviews should be documented and archived by the park.
- The park would benefit from an effort to locate specimens that have already been retrieved and stored in other repositories. Molds of the holotypes

and/or other significant specimens could be made and casts placed in the museum collections. Scientifically significant material encountered in the field should be stabilized in situ or retrieved and curated into dedicated storage if threatened.

Sea Cave Inventory and Monitoring

Cave features are non-renewable 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 FOIA request (see also Appendix B). Some caves are known to occur in areas of high visitor use, such as at Sculptured Beach, close to one of the more popular camp sites where there is easy access along the beach to the caves (Lillian Pearson, Point Reyes National Seashore, intern, email, 23 February 2016).

An official sea cave inventory has not yet been completed for the park. A cave management plan has not yet been completed for Point Reyes National Seashore. Such plans include a comprehensive evaluation of current and potential visitor use and activities, as well as a plan to study known and discover new caves. In order to protect caves as well as visitors, the park should complete a cave inventory and cave management plan. The NPS Geologic Resources Division can facilitate the inventory and development of such a plan. The park could also consider working in conjunction with Golden Gate National Recreation Area because both units will likely have similar cave management needs. With assistance from the Geologic Resources Division, Golden Gate NRA began a sea cave inventory in the summer of 2017 (Ben Becker, Point Reyes National Seashore, science advisor, email, 10 September 2017).

Garret and Williams (2008) produced a sea cave inventory protocol and aerial reconnaissance maps for the coastal area covered by the park, as well as Golden Gate National Recreation Area. The protocol identified equipment and procedures for inventorying sea caves, including how to complete field data sheets, when to collect data to minimize impacts to wildlife, an analysis of job hazards, and pre- and post-field procedures. The reconnaissance maps identified nearly 300 potential sea caves along the coast of Point Reyes National Seashore.

A sea cave inventory could be completed 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 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 ultimately mitigate risks to wildlife and visitor safety.

In the *Geological Monitoring* chapter about caves and associated landscapes, Toomey (2009) 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.

Disturbed Land Restoration

As outlined in the agency's Management Policies (NPS 2006a), National Park Service units are required to "reestablish natural functions and processes in parks unless otherwise directed by Congress. 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, abandoned campgrounds) and/or by agricultural practices (e.g. farming, grazing, timber harvest, abandoned irrigation ditches) to the unimpaired natural conditions. Lands disturbed by human activity often cause unwanted and long-lasting problems that affect other resources.

The NPS use of the term "natural system restoration" recognizes that reaching the former or unimpaired

condition may take many years to decades. Therefore, natural system restoration by the NPS typically involves correcting resource interactions that function unnaturally and ensuring that the directions of the recovery processes are along the proper trajectory, rather than attempting to recreate the end state of an unimpaired natural system.

Though the national seashore and wilderness area retain much natural character, scoping participants pointed out that "there are no areas that haven't been disturbed" by military (e.g., an airstrip), grazing, agricultural and dairy farming, logging, and aborted urban development (e.g., Drakes Beach Estates) (KellerLynn 2008). Mining has also impacted the area (see "Abandoned Mineral Lands" section).

Restoration is fundamentally a multidisciplinary pursuit that involves the understanding of the biological and physical systems and their interactions. Because this report is limited to geologic resource management issues, only restoration projects with a geologic component are discussed. The park's website (www.nps.gov/pore) maintains more information on all of the ongoing and completed restoration projects. Restoration activities related to geologic features or geologic disturbances typically involves removal of artificial structures (e.g., dams, levees) and/or reclamation of abandoned mineral lands (e.g., quarries) by backfilling with native material and revegetation. The next three sections discuss restoration projects involving (1) watersheds and wetlands, (2) dunes, and (3) abandoned mineral lands.

Watersheds and Wetlands Restoration

Several restoration projects are in progress for watersheds and wetlands at the national seashore, many are complete, and many more potential projects exist. Most of these projects are related to restoring lands that were impacted by nearby agriculture. Nearly 25% of the lands in Point Reyes National Seashore are "pastoral" and leased to private operators through agricultural special use permits. Several dairies, one riding stable, and a number of beef cattle ranches are operated under such lease agreements (Ketcham 2001). The leases occur within some of the most sensitive watersheds, including Drakes Estero, Limantour Estero, Abbotts Lagoon, Olema Creek, Pine Gulch Creek, and Tomales Bay (Ketcham 2001). Grazing, agriculture, and recreational use of the waters at Point Reyes National Seashore, and the increased sedimentation and pollution that they cause, pose a substantial threat to resources such as aquatic habitats that support threatened and endangered species, including coho salmon (*Oncorhynchus kisutch*), steelhead trout (*Oncorhynchus mykiss*), and the California red-legged frog (*Rana aurora draytonii*) (Ketcham 1999, 2001). Park managers are working with landowners and the public to facilitate more sustainable use of floodplains.

Giacomini Wetland Restoration Project

The Giacomini wetlands are at the head of Tomales Bay in the Tomales Bay Ecological Reserve. The wetlands are mapped as Qbmo in the GRI GIS data. The wetlands are not within the Point Reyes National Seashore boundary, but are within the Golden Gate NRA boundary; this northernmost area of Golden Gate NRA is managed by Point Reyes National Seashore.

This project restored tidal wetlands from diked agricultural lands. Human alteration began in the 1960s, when logging and agriculture increased sediment delivery to the wetlands. Tidegates and levees installed in 1946 by a large dairy ranch channeled Lagunitas Creek around the wetlands, disconnecting the creek and its tributaries from their floodplains, and greatly reduced their condition and functionality (Parsons and Allen 2015). This area had been the largest integrated tidal marsh complex in Tomales Bay.

Natural wetlands provide many important functions for humans and wildlife, including floodwater retention, water quality improvement, wildlife habitat, and recreational opportunities. Because two-thirds of the Bay's freshwater inflow passes through the project area, these wetlands may have once played an integral role in maintaining health of Tomales Bay, which has deteriorated over the last century because of excessive sedimentation, water and sediment quality problems, non-native species invasions, and other issues (Parsons and Allen 2015).

In 2000, the National Park Service acquired the Waldo Giacomini Ranch for the purpose of wetland restoration using a combination of Congressional appropriations and mitigation funds from the California Department of Transportation. In 2007 and 2008, the NPS restored 248 ha (613 ac) of agricultural lands to the Giacomini wetlands. The restoration activities included the removal of levees, the construction of channels and a flood spill area, the planting of native plants and removal of nonnative plants, and the installation of mitigation ponds for the California red-legged frog (*Rana aurora draytonii*) (Parsons and Allen 2015). Considerations included saltwater intrusion, flooding, habitat migration (multiple listed species were in project area prior to restoration), sea level rise, storm surge, engagement with local community (particularly regarding access) (Parsons and Allen 2015). Once the artificial structures were removed in 2007, this became a "passive" restoration project allowing natural processes to restore the area over time. Material removed during

the construction of the channels and flood spill-area was used to backfill and to reclaim three quarries in the park (see "Abandoned Mineral Lands" section). More information can be found at the restoration project's homepage: https://www.nps.gov/pore/learn/management/planning_giacomini_wrp_restoration.htm.

At the time of this report, the Giacomini Wetlands continue to change . According to models, over the coming years, existing and created channels will continue to increase in size to accommodate flood flows, and new tidal channels will develop, increasing exchange between the restored wetland and Lagunitas Creek and creating more of an equilibrium between tidal inflow and outflow (Parsons and Allen 2015).

Coastal Watershed Restoration Program

The Coastal Watershed Restoration Program restored five coastal watersheds within the park's wilderness area (see https://www.nps.gov/pore/learn/management/planning_cwr.htm). This project removed facilities from wilderness and estuarine areas, and replaced existing road crossings with structures that allow for natural hydrologic process and fish passage for anadromous salmonids (two federally listed threatened species, coho salmon and steelhead trout) and other aquatic species. Part of this project involved the removal of Muddy Hollow Dam and Limantour Beach Pond Dam to return tidal processes to more than 15 acres of coastal marsh habitat in the Estero di Limantour. The project was completed in 2008 (Williams 2009).

Glenbrook Dam

Point Reyes National Seashore completed the Glenbrook Dam Removal Project within the Estero de Limantour in 2009 (fig. 49). The 15-foot high, 600-foot long Lower Glenbrook Dam was constructed in 1960 with material mined from the adjacent hillslopes and failed in 1982 during a major storm. Contractors removed approximately 19,000 cubic yards of the former dam (NPS 2008). The excavation of the remaining dam from the estuary restored a priority abandoned mineral land site (see "Abandoned Mineral Lands" section) in the Phillip Burton Wilderness. The project reestablished the natural hydrologic and shoreline regime in Limantour Estero, a biologically rich estuary that was recently designated a Marine Reserve through the California Marine Life Protection Act. The project area is subject to sea level rise and restoration of natural process within this estuary is a climate change adaptation strategy to ensure maintenance of a healthy and functional estuarine ecosystem (NPS 2008).

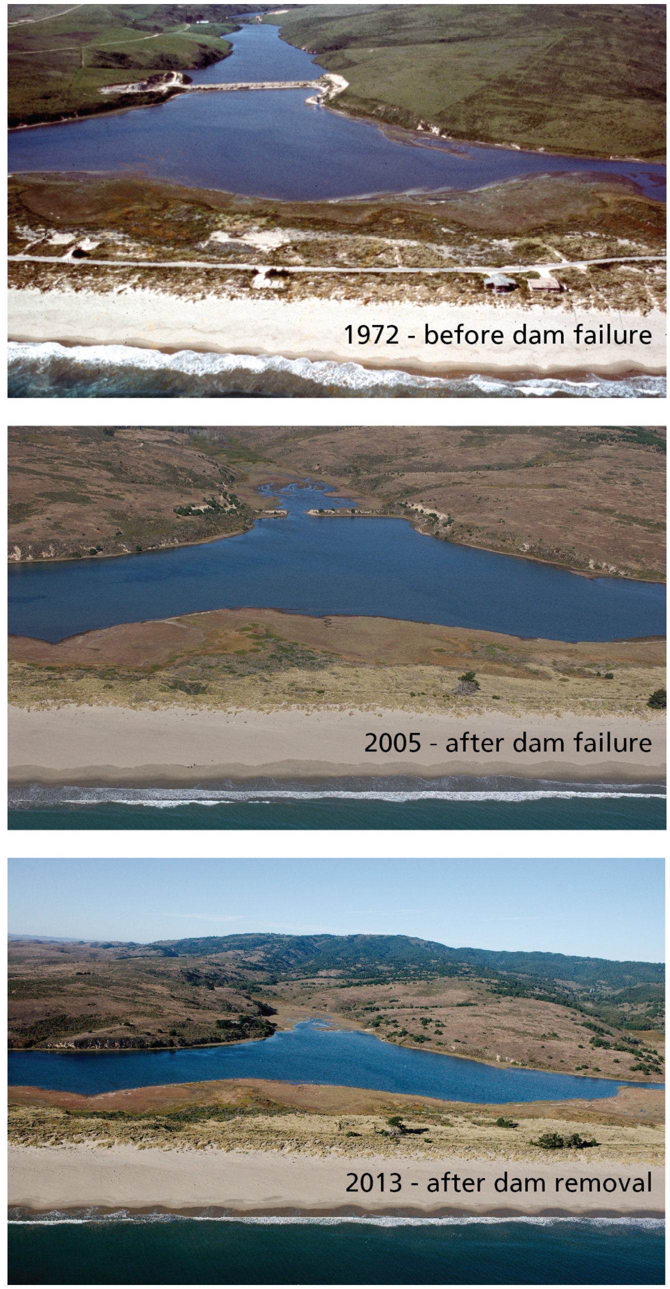


Figure 49. Photographs from before and after the Glenbrook Dam removal.
The dam was built in 1960, failed during a storm in 1982, and was removed in 2009. Photographs copyright © 2002–2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org, used with permission.

Dune Restoration and Monitoring

In 2011, a series of coastal dune restoration projects near Abbott's Lagoon began after more than a decade of planning. The Coastal Dune Restoration Environmental Assessment (NPS 2015) identified several high priority

areas for restoration evaluation: AT&T, B Ranch, North Beach, A Ranch, Davis Property, and Limantour.

Dunes protect the shoreline from the impact of waves and storms and provide habitat for a variety of plants and animals. The park is proposing to restore up to 600 acres of coastal dune habitat primarily to benefit species listed as threatened or endangered. Habitat would be restored by removing highly invasive, non-native plant species (European beachgrass [*Ammophila arenaria*] and iceplant [*Carpobrotus edulis*]) that have greatly altered sand movement, dune structure, and habitat function for native plants and animals. The park's dunes provide habitat for up to 11 federally listed species, however, the primary species using the dunes are the threatened Western snowy plover (*Charadrius alexadrinus nivosus*), the endangered Myrtle's silverspot butterfly (*Speyeria zerene myrtleae*), and the endangered plants, beach layia (*Layia carnosa*) and Tidestrom's lupine (*Lupinus tidestromii*). Other federally listed species that occur in or near dunes or occasionally frequent dune areas include California red-legged frog (*Rana aurora draytonii*), Sonoma alopecurus (*Alopecurus aequalis var. sonomensis*), California least tern (*Sternula antillarum*;), and Willow flycatcher (*Empidonax trailii extimus*) (NPS 2015).

Both European beachgrass and iceplant form dense, monotypic mats or stands. These dense stands alter sand dune structure and function by slowing sand movement and changing sand deposition patterns. In natural communities, dunes continually change in response to sands transported into these systems by waves and wind, typically forming morphologically and floristically distinct foredune and backdune communities. Non-native species and their deep root and rhizome systems armor dune systems and prevent natural migration, which leads to overly large and steeply sloped foredunes and backdunes (Cooper 1936, 1967; Pickart and Sawyer 1998).

Monitoring active dune fields could help park managers determine trends in dune growth and identify areas that require protection or restoration. According to informal observations by Galloway (1997), the belt of sand dunes east of Point Reyes Beach did not change much between 1952 and 1977. Scientific monitoring such as photogrammetry techniques, however, would provide more than anecdotal evidence of change in dune conditions. In the *Geological Monitoring* chapter about eolian features and processes, Lancaster (2009) described the following methods and vital signs for monitoring eolian 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.

Documentation and Reclamation of Abandoned Mineral Lands

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

According to the NPS Abandoned Mineral Lands (AML) database and Burghardt et al. (2014), the park contains 47 AML features associated with clay, sand and gravel quarries spread across the Point Reyes Peninsula. Features include historic lime kilns, surface mines, waste rock, and highwalls. Most surface mines are small cuts into Quaternary marine terraces, alluvial, and dune deposits. Some are on fenced grazing land while others are near hiking trails. AML features pose 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, some of which may be protected under the Endangered Species Act or state species listings. Resource management of AML features requires an accurate inventory and reporting. All AML features should be recorded in the Servicewide AML Database (the NPS Geologic Resources Division will provide assistance). An accurate inventory identifies human safety hazards and contamination issues, and facilitates closure, 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. Four features have already been mitigated and one still requires mitigation (as of the completion of the servicewide AML inventory on 31 December 2013). The NPS AML website, http://go.nps.gov/aml, provides further information.

Previous involvement by the Geologic Resources Division with disturbed lands in the park included technical evaluation and planning guidance for the closure of eight open pit quarries. In August 2006, Dave Steensen from the GRD mapped and inventoried

the quarries to determine volume and shape of the area requiring reclamation. As of 2008, when the scoping summary was prepared, park managers had administratively closed the more than 30 borrow pits in the park and had plans to restore those that posed safety risks (KellerLynn 2008). Most of the closed borrow pits had naturally revegetated, however, seven open pit quarries with 20 to 50 foot vertical walls that impacted the viewshed, posed a safety hazard to ranchers and park visitors, and acted as vectors for invasive plants (DiGregoria 2008). The quarries had been used by ranchers for maintenance purposes and had been administratively closed since the early 1990s, but evidence of continued use was document by NPS staff in some locations (DiGregoria 2008). Three of the quarries were filled with material from the Giacomini Wetlands Restoration Project and capped with native quarried material, top soil, and then reseeded; the remaining quarries were regraded and/or revegetated (DiGregoria 2008). Six of the quarries were restored to a natural state, and the seventh was recontoured and incorporated into silage production at the McClure Dairy (DiGregoria 2008). In 2009, material from removal of the lower Glenbrook Dam was used to reclaim the Glenbrook Quarry (see also "Disturbed Lands Restoration").

Soil erosion and run off from the abandoned Gambonini Mine—a 5-ha (12-ac) site on a steep hillside—was sending as much as 82 kg (180 lbs) of mercury per year into Salmon and Walker Creeks and ultimately into Tomales Bay. In 2005, the Marin Conservation Corps, U.S. Environmental Protection Agency, and San Francisco Bay Regional Water Quality Control Board completed a six-year restoration effort. Inorganic (total) mercury concentrations in sediment at the Walker Creek Delta have been in decline since the project began. From 2000 to 2012, mean total mercury concentrations declined from 1.6 mg/kg to 0.9 mg/kg (San Francisco Bay Regional Water Quality Control Board 2012). The total maximum daily load (TMDL) for mercury in the Walker Creek Watershed is 0.5 mg/kg (San Francisco Bay Regional Water Quality Control Board 2008). According to the most recent report from the San Francisco Bay Regional Water Quality Control Board (2008), the total mercury in Walker Creek is expected to decrease to at least the TMDL and may eventually reduce to the background concentration of 0.2 mg/kg, though a time frame for this anticipated decline was not reported. Infrequent large storms disturb mining waste still caught in depositional areas along Walker Creek causing episodic mercury rises in delta sediments; however, these pulses will continue to decrease and eventually cease as storms remove all of the mining waste caught in Walker Creek (San Francisco Bay Regional Water Quality Control Board 2012).

Conventional Energy and Mineral Development and Extraction

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.

Non-administrative (not conducted by the park) sand and gravel extraction occurs in the park (Julia Brunner, policy and regulatory specialist, NPS GRD personal communication, 23 January 2017). The quarries had been administratively closed since the early 1990s, but evidence of continued use was documented by NPS staff in some locations (DiGregoria 2008). Glauconite—greensand—occurs in considerable concentrations in the Purisima Formation. Glauconite is a mineral used for softening water and in fertilizers. There are no reports that the material in this location was ever exploited commercially (Galloway 1977). Scheelite, an ore of tungsten, is associated with the metamorphosed limestone in map unit **MZPZmx** (Galloway 1977). It also has never been exploited commercially.

History of Energy and Mineral Activities in the Park

The first documented energy and mineral activities in the park occurred in the mid-1800s. With the exception of sand and gravel quarrying, all activities had ceased by the mid-1900s. Most energy and mineral activities were short lived and never profitable, such as the Olema Lime Kilns which operated for less than 5 years in the mid-1800s (fig. 50). Table 13 lists energy and minerals activities documented in the park.

Figure 50. Photograph of the Olema Lime Kilns ruins in 1934.
Built in 1850 and abandoned in 1855, only a stone wall ruin and two arched fireboxes remain of a three-kiln operation in the Olema Valley. Public domain photograph from the Historic American Buildings Survey of California. Library of Congress, Prints & Photographs Division, CA-1437-1, available at https://en.wikipedia.org/wiki/Olema_Lime_Kilns#/media/File:Lime_Kiln_(Olema,_CA).jpg.

Table 13. History of energy and mineral activities in Point Reyes National Seashore.

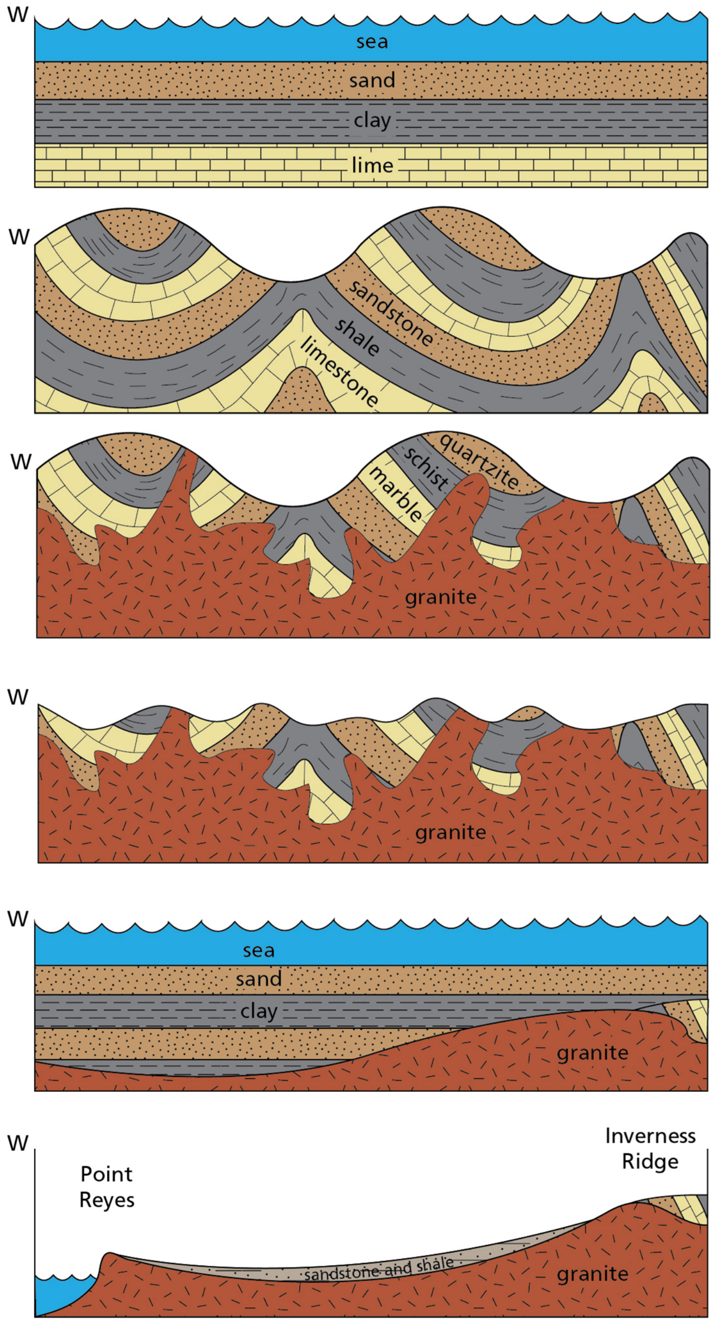
Note: data from Galloway (1977); Stoffer (2006); NPS (2017); GRI conference call participants (Appendix B).

Date	Activity	Description
1854	Granite quarry	A quarry at the east end of the Point Reyes Headlands briefly supplied weathered granite for use as road material.
Late 1800s	Coal prospects	No additional information available
Late 1800s	Gold placer deposits	Deposits observed on some streams and beaches.
1850–1855	Olema lime kilns	Low quality of limestone, limited supply, and a poor economy forced the abandonment of the kilns by 1855. Today, the ruins are on the National Register of Historic Places in Marin County and listed as California State Historical Landmark no. 222 (fig. 50).
1863–1918	Copper mining	Three companies operated on the slopes of Bolinas Ridge. Low copper prices and high transportation costs for smelting limited profitability. The last company to close was the Chetco Mining Company, in 1918.
Mid-1800s to mid-1900s	Petroleum exploration	Oil and gas seeps in the Monterey Formation and thick tar- and oil-sands at the Miocene-Pliocene contact were investigated. More than 10 exploration wells were drilled on Point Reyes, none of which located commercially viable oil or gas. According to Galloway (1977), "a spectacular gas seep in the Duxbury Point area…apparently was big enough to cook fish on when lighted", however, it "is not evident today."

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 Golden Gate NRA. 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, eolian processes, viewsheds, habitats and biological resources, underwater sea waves, and cultural landscapes.



Prior to the Late Cretaceous

Layers of sand, clay, and lime accumulated in a shallow sea.

Late Cretaceous

Sedimentary layers compacted into soft rocks, then folded, and eroded when the land was elevated above the sea.

Late Cretaceous

Pressure and heat of magma which intruded the soft rocks changed them into hard metamorphic rocks (MZPZmx). The magma cooled to form granite (Kg, Kgri, Kgdt).

Late Cretaceous to Eocene

Partial erosion of metamorphosed rock exposed granite, leaving pendants of former roof rock.

Tertiary

Granite was covered by layers of new sediments ("T" map units) when ocean covered the land.

Quaternary

Granite again exposed by wind and water erosion of sediments following reemergence of the land mass.

Figure 51. Sequential cross section illustrations of the general geologic history of the park. Graphic by Rebecca Port, redrafted from Galloway (1977, figure 5, p. 80).

Geologic History

This chapter describes the chronology of geologic events that formed the present landscape.

Ancient Convergent Boundary

The landmass of California began assembling at the end of the Ordovician Period, more than 400 million years ago. An oceanic tectonic plate was converging with the western edge of the North American continent. As plate convergence occurred (throughout the Paleozoic Era), rocks were towed toward the mainland and accreted to the continent. The collision also built mountains in Nevada and Idaho and uplifted the Ancestral Rocky Mountains. By 200 million years ago (beginning of the Jurassic Period), the California landmass had grown to about where the Sierra Nevada foothills are today, approximately 160 km (100 mi) east of the modern shoreline. Much of California was under water. The oldest rocks in the park (**MZPZmx**; see "Older Metamorphic Rocks" section) were originally deposited in a shallow sea over California as limestone, shale, and sandstone (fig. 51; Galloway 1977). The timing of deposition is not known other than it must have occurred before about 80 million years when the Cretaceous granitic rocks that now surrounds them formed in association with an ancient subduction zone (table 14).

Franciscan Subduction

When an oceanic and continental tectonic plate converge, the denser and thinner oceanic plate sinks beneath the lighter continental plate at what is termed a "subduction zone." Though plate convergence had been occurring along the California coast since the Ordovician Period (more than 400 million years ago), geologists refer to the period of convergence from about 160 million to 50 million years ago as "Franciscan subduction" because enough geologic evidence remains from this time period to draw significant conclusions about the history and timing of events. During Franciscan subduction, the Farallon plate—an ancient oceanic plate—converged with and sank beneath the western edge of the North American continental plate. Certain geologic settings, such as an oceanic trench, forearc basin, and volcanic arc typically develop along a subduction zone (fig. 52).

Franciscan Complex rocks ("**Kf**" and "**KJf**" map units) underlie most of Golden Gate NRA but are only mapped in a few very small locations in the park near the San Andreas Fault. These rocks assembled as an "accretionary wedge" from scraped off bits of the Farallon plate and turbidites (underwater landslide deposits) in the deep oceanic trench which formed between the two plates. See Port (2016) and Elder (2013) for a more comprehensive discussion of Franciscan subduction and Franciscan Complex rocks.

The Cretaceous granitic basement rocks underlying the park formed about 80 million years ago as part of a volcanic arc associated with the Franciscan subduction zone (table 14). The subduction of the Farallon plate triggered melting in the mantle, which ultimately produced an extensive volcanic arc system known as the Sierran arc (fig. 52). Where the subducting oceanic plate reached a depth of about 100 to150 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 (fig. 52). Batholiths that fueled those volcanoes now comprise the basement rock of the Point Reyes Peninsula (**Kg**, **Kgri**, **Kgdt**) as well as the iconic granitic landscapes of Yosemite National Park (see GRI report by Graham 2012). Heat from the magma of the batholith metamorphosed overlying layers of limestone, shale, and sandstone into marble, mica schist, and quartzite, respectively (**MZPZmx**).

The granitic basement rocks of the Point Reyes Peninsula did not form in their current location. They originated in Southern California near the Tehachapi Mountains [500 km (300 mi) south of their current location] from the same massive batholith that forms the core of the Peninsular Ranges in Mexico. Around 50 million years ago, Franciscan subduction was coming to an end as the Farallon plate was consumed entirely and the convergent boundary began to be replaced by a transform plate boundary (table 14). A portion of southwestern California, including the area of the park, was captured by the Pacific plate on the west side of this new boundary and started to move laterally up the coast.

Transition to a Transform Boundary

The east-moving Farallon plate was intermediary between the Pacific and North American tectonic plates. Where subduction fully consumed the Farallon plate, the Pacific and North American plates came into contact and the boundary type transitioned from convergent to transform (see "Geologic Setting" section). The Pacific plate was moving northwest; therefore, when it came together with the North

Table 14. Sequence of major geologic events at Point Reyes National Seashore

Note: Sequence of events derived from Galloway (1977) and Stoffer (2006).

Time Period	Geologic Setting	Distance From Current Park Position	Map Unit(s)	Event(s)
Paleozoic and (or) Mesozoic (before ~80 MYA)	Shallow sea	unknown	MZPZmx	Oldest rocks in the park were originally deposited as layers of sand, clay, and lime (calcium carbonate) in shallow seas.
Late Cretaceous (~80 MYA)	Convergent plate boundary	500 km (300 mi)	Kg, Kgri, Kgdt, MZPZmx	Magma intruded overlying sedimentary rocks and cooled to form granitic basement. Sedimentary rocks were metamorphosed to schist, quartzite, and marble.
Late Cretaceous to Eocene (80 MYA to 50 MYA)	Marine regression Uplift of land to form mountains	Less than 500 km (300 mi)	Kg, Kgri, Kgdt, MZPZmx	Metamorphosed rocks partly eroded and exposed granitic basement, leaving pendants of former roof rock.
Eocene (~50 MYA)	Marine transgression Transform plate boundary	Between 500 km and 156 km (300 mi and 97 mi)	Tpr	A portion of the peninsula became submerged. Turbidite sequences were deposited in submarine channels on the submerged portions of the peninsula. The Point Reyes Conglomerate is part of one of those sequences.
Oligocene (~30 MYA)	Marine regression	n/a	n/a	Some of the turbidite deposits were exposed by the drop in sea level and eroded.
Miocene (~25 MYA to 10 MYA)	Marine transgression Transform plate boundary	Between 500 km and 156 km (300 mi and 97 mi)	Tsc, Tsm, Tm, Tls	Entire peninsula became submerged. There was widespread deposition of the Laird Sandstone in shallow water. Shale of the Monterey Formation was deposited farther offshore in the deeper water covering the peninsula. Younger Miocene deposits (Santa Margarita Sandstone and Santa Cruz Mudstone) are much more widespread than older, indicating continued submergence of peninsula
Late Miocene to Pliocene (~10 MYA to 5 MYA)	Marine regression Transform plate boundary	156 km (97 mi) (near Point Lobos)	Tps	The northern part of peninsula was exposed and younger Miocene beds (Santa Margarita Sandstone and Santa Cruz Mudstone) in that area eroded. The Purisima Formation was deposited on the still-submerged, southern part of the peninsula in a shallow sea.
Quaternary (2.58 MYA to 130,000 years ago)	Marine regression Quaternary glaciation Transform plate boundary	Less than 156 km (97 mi)	Qoc, Qml, QTm	The current ice age began. Sediments changed from shallow sea to beach and lake deposits. Deposition occurred in the depression occupied by the San Andreas Fault near Bolinas.
Pleistocene (130,000 to 110,00 years ago)	Marine transgression Sangamon interglacial stage Transform plate boundary	Less than 156 km (97 mi)	None documented.	Melting of ice caps raised sea level everywhere and caused the marine incursion which formed the wave-cut platform between Bolinas and Drakes Bay.
Pleistocene (110,000 to 11,700 years ago)	Marine regression Wisconsin glaciation Transform plate boundary	Less than 156 km (97 mi)	Qls, Qobs, Qoal, Qtmr, Qmst	Marine terraces formed when the wave-cut platforms were exposed above sea level. Terrestrial deposits of Monterey Formation sediments washed down from nearby hills and covered the terraces.
Holocene (Past 11,700 years)	Marine transgression Interglacial stage Transform plate boundary	0 km (0 mi)	Qbs, Qdsy, Qalo, Qbmo, Qls	The sea rose about 120 m (390 ft) to modern day levels and eroded the marine terraces back to a small fragment of the area probably once occupied during the last ice age.

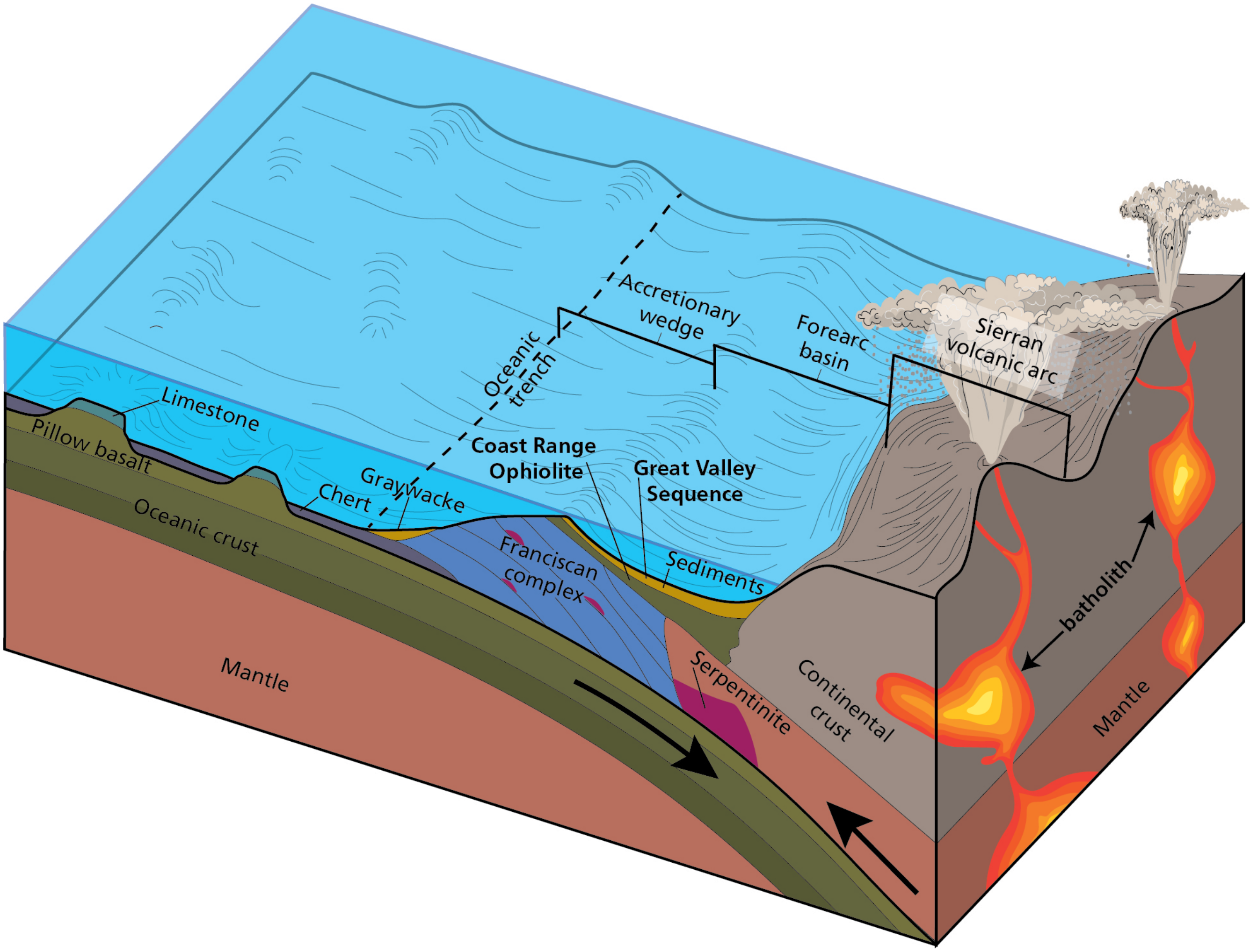


Figure 52. Illustration of the Franciscan subduction zone.
The Cretaceous granitic basement rocks in the park were initially emplaced as part of a batholith in the Sierran arc associated with a subduction zone. The Franciscan Complex which makes up the basement rocks on the California mainland, east of the park were part of an accretionary wedge which formed when basalt, chert, and limestone traveled into the oceanic trench and were topped off by sediments eroded from the land (mainly graywacke sandstone turbidites). 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. Arrows show relative movement along faults See GRI report by Port (2016) for more information about the Franciscan Complex. Graphic by Trista Thornberry Ehrlich (Colorado State University) modified from Elder (2001, figure 3.3).

American plate, relative plate motion changed from plates colliding (convergent) to plates sliding past each other (transform). Little is known about the fault systems which developed between about 50 million and 30 million years ago during the beginning of this complex tectonic transition. There is evidence that lateral displacement (northward on the Pacific Plate) occurred during this time (Stoffer 2006).

Roughly 30 million years ago, the San Andreas Fault, which is locally considered to represent the plate boundary though this is a simplified view (see "Faults" section) originated near modern-day Los Angeles. This occurred at a point called the Mendocino triple junction—the location where the Farallon, Pacific, and North American plates intersected (fig. 53). As the Farallon plate continued to be consumed by subduction, the Mendocino triple junction migrated northward. The transform boundary between the

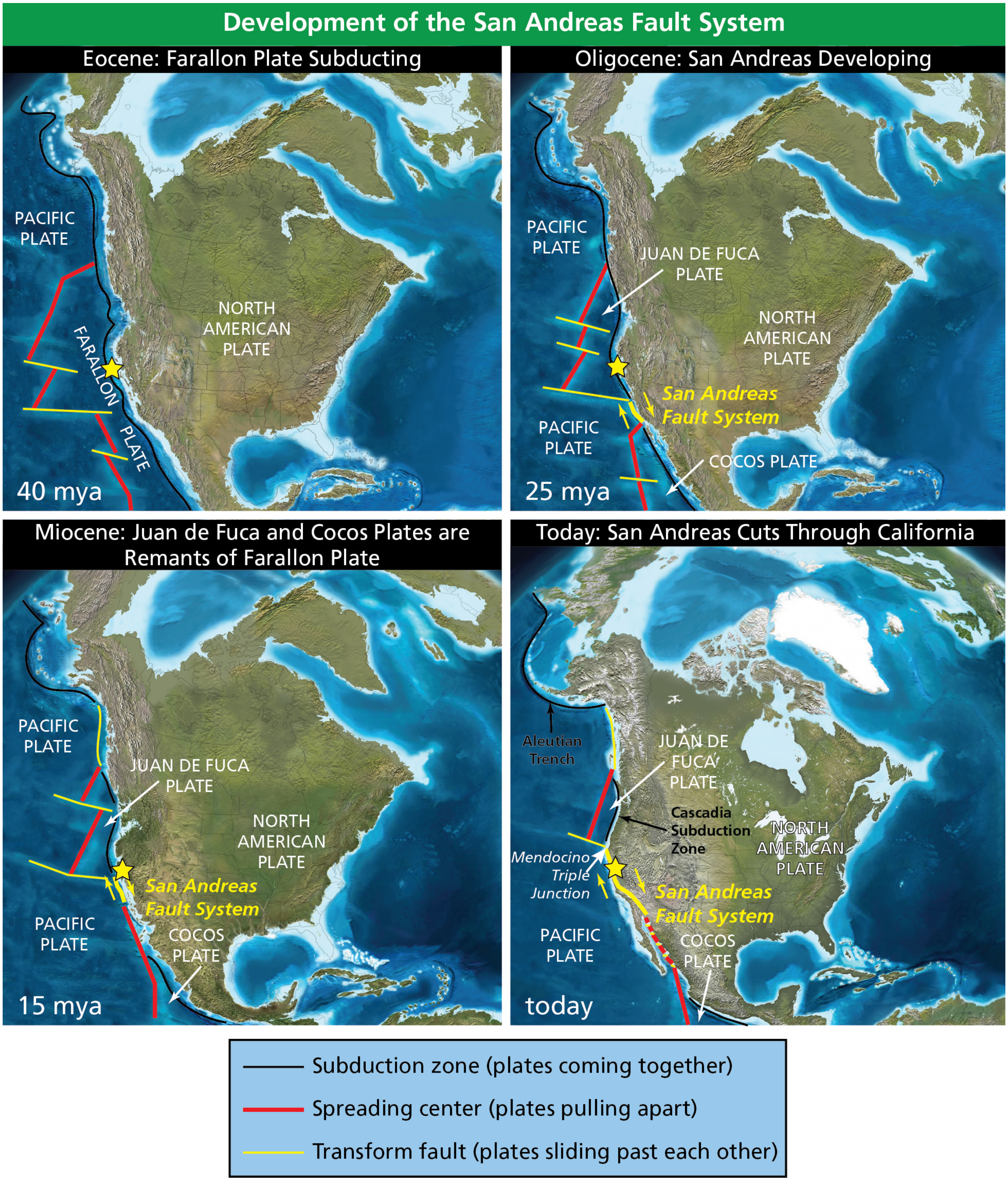


Figure 53. Paleogeographic maps of the growth of the San Andreas Fault system. When the spreading center between the Pacific and Farallon plates intersected the North American plate, a transform fault (San Andreas Fault system) formed, causing strike-slip movement. Yellow stars indicate the approximate location of the park. Base paleogeographic maps by Ron Blakey (Colorado Plateau Geosystems, Inc.). Annotations by Rebecca Port and Jason Kenworthy (NPS).

Pacific and North American plates and coincident San Andreas Fault developed behind it and lengthened as the junction migrated north, reaching the San Francisco Bay Area between 15 million and 12 million years ago (Atwater 1970, 1989; Page and Wahrhaftig 1989; Stoffer 2006). Fragments of the Farallon plate—the Explorer, Juan de Fuca, and Gorda plates—are still subducting off the coast of northern California, Oregon, and Washington (Cascadia Subduction Zone), and southern Alaska (Aleutian Trench) (fig. 4). Active volcanoes of the Cascade Range and Aleutians mark the locations of these modern subduction zones.

The Salinian block, which underlies the park (see "Salinian Block" section), represents a sliver of a massive batholith that formed in the ancient convergent setting and was later sliced of and carried north by the Pacific tectonic plate along the modern transform boundary.

Development of the Salinian Block

Today, the Salinian Block is an extensive belt of granitic rocks (fig. 9; see "Salinian Block" section). This now-elongated block was a more compact entity during the time of its formation roughly 80 million years ago near the latitude of the Tehachapi Mountains and Mojave Desert, nearly 500 km (300 mi) south of the park's current location. Movement along the transform boundary transported the rocks north. However, they did not travel as one cohesive mass but rather in slivers with movement accommodated by many strike-slip faults, including the San Andreas. Similar to the way a fan unfolds, the once compact granitic mass became elongated and stretched by numerous faults (fig. 9). The granitic basement rocks in the park along with those on Bodega Head are now the northernmost occurrence of Salinian rocks and therefore have been displaced the farthest. Other occurrences include granitic rocks on Montara Mountain and those of the Gabilan Range.

Little is known about the faults responsible for the earliest displacements within the Salinian Block. The portion of the block which makes up the Point Reyes Peninsula was probably attached to Salinian rocks underlying Montara Mountain and moving north as a unit with them from at least 50 million years ago until about 10 million years ago based on evidence from sedimentary sequences deposited on top of the basement rocks. The approximately 50 million year old Point Reyes Conglomerate (**Tpr**) is nearly identical to the Carmelo Formation of Point Lobos and the late Miocene to Pliocene sedimentary sequence in the park (**Tsm**, **Tsc**, **Tps**) is almost identical to a sequence in the Santa Cruz Mountains (Clark et al. 1984; Clark and Brabb 1997; Stanley and Lillis 2000). This indicates the Point Reyes area must have been connected to the Point Lobos area throughout this time, keeping in mind that they were all still moving north from their place of origin near the Tehachapi Mountains.

Movement of the Point Reyes Peninsula

The Point Reyes Peninsula as we know it formed about 10 million years ago (late Miocene time) when the San Gregorio Fault sliced it off from Point Lobos and began transporting it northward at a faster rate than Point Lobos was moving north. In the past 10 million years, the Point Reyes Peninsula has moved about 156 km (97 mi) along the San Gregorio Fault from near Point Lobos to its current position (Clark et al. 1984; Dickinson et al. 2005). The San Gregorio Fault runs from Monterey Bay, through the western Santa Cruz Mountains, and offshore to Bolinas where it converges with the San Andreas Fault (Greene et al. 1973). Today, the Point Reyes Peninsula is immediately adjacent to and moving with the San Andreas Fault.

Dynamic Coast

The rocks and sediments on top of the Cretaceous granitic basement record variations in depositional environments resulting from changes in sea-level, climate, and tectonics (Woodley and Grove 2010). At some point after 80 million years ago (when the Cretaceous granite formed) the granite (**Kg**, **Kgri**, **Kgdt**) and surrounding metamorphic rocks (**MZPZmx**) were lifted up and began to erode. Around 50 million years ago (Eocene Epoch) sea level rose and the eroded granitic rocks, plus rounded volcanic clasts (origin unknown since rock like this is not present in area anymore) were deposited as conglomerate (**Tpr**) on top of the Cretaceous granitic basement. This conglomerate is not present on top of the basement rock on Inverness Ridge; this suggests that the peninsula was sufficiently elevated during Eocene time that sediments could not be deposited everywhere (Galloway 1977).

From the Eocene forward, rocks in the park generally reflect periods of sea level rise (when marine sediments were deposited) separated by unconformities representing periods of sea level drop when erosion or non-deposition occurred. Table 14 describes the changes in sea level reflected in the rocks over the last 50 million years. During most of the Miocene Period sea level was relatively high and sand, shale, and mudstone of the Laird Sandstone (**Tls**), Monterey Formation (**Tm**), Santa Margarita Sandstone (**Tsm**), and Santa Cruz Mudstone (**Tsc**) were deposited. The youngest Miocene rocks (**Tsm** and **Tsc**) are the most widespread, indicating sea level was rising through much of that time (Galloway 1977). Sea level fell at the end of the Miocene (5–10 million years ago); the transgression was most pronounced in the northern part of the peninsula

where young Miocene rocks were eroded (Galloway 1977). Sediments deposited on the southern half of the peninsula (**Tps**) reflect a gradually shrinking sea. Since 5 million years ago, the area has been primarily above sea level and subject to weathering and erosion, shedding sediments into the surrounding seas and valleys that may eventually become sedimentary rocks themselves.

The current ice age (called the "Quaternary glaciation") consisting of a series of glacial (cool) and interglacial (warm) cycles began approximately 2.58 million years ago. Sea level change during each cycle of glaciation was in the range of 50 to 150 m (160 to 500 ft) (Stoffer 2002). Cores taken from San Francisco Bay during bridge-foundation studies recorded as many as seven interglacial cycles (indicated by estuarine rocks which correspond to times of high sea level) over the last 500,000 years (Atwater et al. 1977; Sloan 1989).

The most recent glacial stage (called the "Wisconsin glaciation") lasted from about 110,000 to 11,700 years ago. Around 26,000 years ago, at the Last Glacial Maximum—when ice sheets reached their greatest extent—sea level was as much as 120 m (390 ft) lower than it is today and the coastline was about 35 km (22 mi) to the west (fig. 54; Galloway 1977; 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). Sea level began to rise toward the end of the last glacial stage, about 21,000 years ago.

The beginning of the Holocene Period (11,700 years ago) marked the transition to an interglacial stage, which is still ongoing. Sea level rise was rapid [about 9 to 11 m (30 to 36 ft) per thousand years] until about 7,000 years ago, when it slowed considerably to about 1 m (3 ft) per thousand years (Peltier and Fairbanks 2006; Stanford et al. 2011)]. 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). Sea level rise also led to broadening of the continental shelf, progressive eastward migration of the shoreline and wave-cut platform, and associated transgressive erosion and deposition. (Johnson et al. 2015). 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).

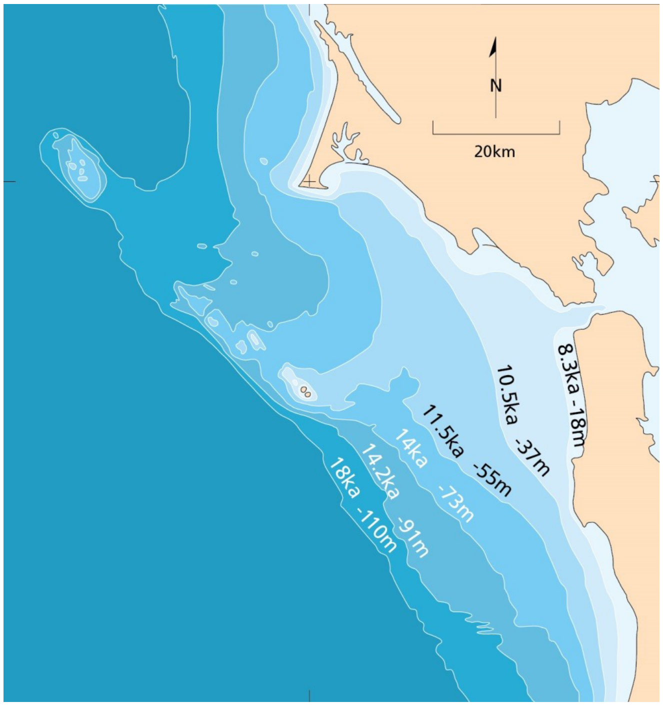


Figure 54. Map of sea level fluctuations.
Since the last major global glaciation, which ended about 20,000 years ago, sea level has risen. A particularly long period of sea-level stability occurred about 11,500 years ago (as indicated by a thick, widespread accumulation of nearshore gravel and sand). Afterward, sea level again began to rise. USGS map by K. R. Lajoie after Anderson et al. (2001, figure 4.6).

Geologic Map Data

A geologic map in GIS format is the principal deliverable of the GRI program. GRI GIS data produced for the park follows the source maps listed here and includes components described in this chapter. A poster (in pocket) displays the data over imagery of the park and surrounding area. Complete GIS data are available at the GRI publications website: http://go.nps.gov/gripubs.

Geologic Maps

A geologic map is the fundamental tool for depicting the geology of an area. Geologic maps are two-dimensional representations of the three-dimensional geometry of rock and sediment at or beneath the land surface (Evans 2016). Colors and symbols on geologic maps correspond to geologic map units. The unit symbols consist of an uppercase letter indicating the age (see fig. 5) and lowercase letters indicating the formation's name. Other symbols depict structures such as faults or folds, locations of past geologic hazards that may be susceptible to future activity, and other geologic features. Anthropogenic features such as mines or quarries, as well as observation or collection locations, may be indicated on geologic maps. The American Geosciences Institute website, http://www.americangeosciences.org/environment/publications/mapping, provides more information about geologic maps and their uses.

Geologic maps are typically one of two types: surficial or bedrock. Surficial geologic maps encompass deposits that are unconsolidated and formed during the past 2.6 million years (the Quaternary Period). Surficial map units are differentiated by geologic process or depositional environment. Bedrock geologic maps encompass older, more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type. The GRI produced a bedrock map for Point Reyes National Seashore. Prominent surficial units such as beach and dune deposits are included on the bedrock map.

Source Maps

The GRI team does not conduct original geologic mapping. The team digitizes paper maps and compiles and converts digital data to conform to the GRI GIS data model. The data is available at the GRI publications website: http://go.nps.gov/gripubs. The GRI GIS data set includes 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. These items are included in the goga_geology.pdf. The GRI GIS data covers Point Reyes National Seashore, and areas east of Point Reyes south to the Marin Headlands and the Golden Gate, including Golden Gate National Recreation Area and Muir Woods National Monument, Fort Point National Historic Site, and much of San Francisco. A component dataset limited to the Marin Headlands and Point Reyes areas is also available for download at the GRI publications website. The GRI team used the following sources to produce the GRI GIS data set for Point Reyes National Seashore and to provide information for this report:

- Schlocker et al. (1958)
- Pampeyan (1994)
- Clark and Brabb (1997)
- Bonilla (1998)
- Blake et al. (2000)
- Brabb et al. (2000)
- Wagner et al. (2006)

GRI GIS Data

The GRI team standardizes map deliverables by using a data model. The GRI GIS data for Point Reyes National Seashore was compiled using data model version 2.1, which is available 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 Geologic Maps website, http://go.nps.gov/geomaps, provides more information about the program's map products.

GRI GIS data are available on the GRI publications website http://go.nps.gov/gripubs and 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 data set:

- 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 4);
- 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;
- An ESRI map document (mhpr_geology.mxd) that displays the GRI GIS data; and

GRI Map Poster

A poster of the GRI GIS draped over a shaded relief image of the park and surrounding area is included with this report. Not all GIS feature classes are included on the poster (table 4). Geographic information and selected park features have been added to the poster. 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 GRI for assistance locating these data.

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 on the poster. Based on the source map scales of (1:24,000), (1:48,000), (1:75,000), and (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), 24 m (80 ft), 38 m (125 ft), and 51 m (167 ft), respectively, of their true locations.

Table 15. GRI GIS data layers with features in Point Reyes National Seashore.

Note: Additional layers are present in the data but do not have features mapped in Point Reyes National Seashore.

Data Layer	On Poster?
Geologic Attitude Observation Localities	No
Hazard Feature Lines	Yes
Faults	Yes
Folds	Yes
Mélange Blocks	No
Geologic Contacts	Yes
Geologic Units	Yes

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

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Additional References

These references, resources, and websites may be of use to resource managers. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.

Geology of National Park Service Areas

- 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 Geoscientist-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

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, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado): http://go.nps.gov/geomonitoring
- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): https://www.nps.gov/dsc/technicalinfocenter.htm

Climate Change Resources

- NPS Climate Change Response Program Resources: http://www.nps.gov/subjects/climatechange/resources.htm
- NPS Coastal Adaptation: https://www.nps.gov/subjects/climatechange/coastaladaptation.htm
- US Global Change Research Program: http://www.globalchange.gov/home
- US Geological Survey Coastal Change Hazards Portal: https://marine.usgs.gov/coastalchangehazardsportal/
- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/
- California Coastal Commission: https://www.coastal.ca.gov/
- California Coastal Conservancy: http://scc.ca.gov/

Geological Surveys and Societies

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

US Geological Survey Reference Tools

- National geologic map database (NGMDB): http://ngmdb.usgs.gov/ngmdb/ngmdb_home.html
- Geologic names lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/search
- Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/
- GeoPDFs (download 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/

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- Wallace, R. E., editor. 1990. The San Andreas Fault system, California. Professional Paper. US Geological Survey, Washington, DC.

California Earthquake Information

- California Geological Survey, earthquakes: http://www.conservation.ca.gov/cgs/geologic_hazards/earthquakes
- USGS, earthquake information by region: https://earthquake.usgs.gov/earthquakes/byregion/california.php
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Appendix A: Scoping Participants

The following people attended the GRI scoping meeting, held on 26-28 September 2007, or the follow-up report writing conference call, held on 23 February 2016. 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

Note: based on information provided at the time of the scoping meeting.

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	Point Reyes NS-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	US 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

2016 Conference Call Participants

Name	Affiliation	Position
Rebecca Beavers	NPS Geologic Resources Division	Geologist, Coastal Geology & Adaptation Coordinator
Benjamin Becker	Point Reyes National Seashore	Science Advisor / Marine Ecologist
Erica Clites	UC Berkeley	Museum Scientist, USGS Invertebrate Collections
Will Elder	Golden Gate National Recreation Area	Visual Information Specialist
Samuel Johnson	US Geological Survey	Research Geologist
Jason Kenworthy	NPS Geologic Resources Division	Geologist, GRI Reports Coordinator
Lillian Pearson	Point Reyes National Seashore	Geoscientists-in-the-Parks intern
Wendy Poinsot	Point Reyes National Seashore	Fire Program Environmental Planner
Rebecca Port	NPS Geologic Resources Division	Geologist, GRI Report Author
Harold Pranger	NPS Geologic Resources Division	Chief, Geologic Features and Systems Branch
Chris Wills	California Geological Survey	Supervising Engineering 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 NPS minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of December 2017. Contact the NPS Geologic Resources Division for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester. **National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of cave and karst resources. **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be cancelled with appropriate compensation; and lands are withdrawn from mineral entry.	**36 CFR § 2.1** prohibits possessing/ destroying/disturbing…cave resources…in park units. **43 CFR Part 37** states that all NPS caves are "significant" and sets forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/ adjacent to wilderness.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Paleontology	**National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa et seq.** provides for the management and protection of paleontological resources on federal lands.	**36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted. **43 CFR Part 49** (in development) will contain the DOI regulations implementing the Paleontological Resources Preservation Act.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.
Recreational Collection of Rocks Minerals	**NPS Organic Act, 54 USC. § 100101 et seq.** directs the NPS to conserve all resources in parks (which includes rock and mineral resources) unless otherwise authorized by law. **Exception: 16 USC. § 445c (c)** Pipestone National Monument enabling statute. Authorizes American Indian collection of catlinite (red pipestone).	**36 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units. **Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown. **Exception: 36 C.F.R. § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, and Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Geothermal	**Geothermal Steam Act of 1970, 30 USC. § 1001 et seq. as amended in 1988**, states • No geothermal leasing is allowed in parks. • "Significant" thermal features exist in 16 park units (the features listed by the NPS at **52 Fed. Reg. 28793-28800** (August 3, 1987), plus the thermal features in Crater Lake, Big Bend, and Lake Mead). • NPS is required to monitor those features. • Based on scientific evidence, Secretary of Interior must protect significant NPS thermal features from leasing effects. **Geothermal Steam Act Amendments of 1988, Public Law 100--443** prohibits geothermal leasing in the Island Park known geothermal resource area near Yellowstone and outside 16 designated NPS units if subsequent geothermal development would significantly adversely affect identified thermal features.	None applicable.	**Section 4.8.2.3** requires NPS to • Preserve/maintain integrity of all thermal resources in parks. • Work closely with outside agencies. • Monitor significant thermal features.
Mining Claims (Locatable Minerals)	**Mining in the Parks Act of 1976, 54 USC § 100731 et seq.** authorizes NPS to regulate all activities resulting from exercise of mineral rights, on patented and unpatented mining claims in all areas of the System, in order to preserve and manage those areas. **General Mining Law of 1872, 30 USC § 21 et seq.** allows US citizens to locate mining claims on Federal lands. Imposes administrative and economic validity requirements for "unpatented" claims (the right to extract Federally-owned locatable minerals). Imposes additional requirements for the processing of "patenting" claims (claimant owns surface and subsurface). Use of patented mining claims may be limited in Wild and Scenic Rivers and OLYM, GLBA, CORO, ORPI, and DEVA. **Surface Uses Resources Act of 1955, 30 USC § 612** restricts surface use of unpatented mining claims to mineral activities.	**36 CFR § 5.14** prohibits prospecting, mining, and the location of mining claims under the general mining laws in park areas except as authorized by law. **36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart A** requires the owners/operators of mining claims to demonstrate bona fide title to mining claim; submit a plan of operations to NPS describing where, when, and how; prepare/submit a reclamation plan; and submit a bond to cover reclamation and potential liability. **43 CFR Part 36** governs access to mining claims located in, or adjacent to, National Park System units in Alaska.	**Section 6.4.9** requires NPS to seek to remove or extinguish valid mining claims in wilderness through authorized processes, including purchasing valid rights. Where rights are left outstanding, NPS policy is to manage mineral-related activities in NPS wilderness in accordance with the regulations at **36 CFR Parts 6 and 9A**. **Section 8.7.1** prohibits location of new mining claims in parks; requires validity examination prior to operations on unpatented claims; and confines operations to claim boundaries.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Nonfederal Oil and Gas	**NPS Organic Act, 54 USC § 100751 et seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). Individual Park Enabling Statutes: • **16 USC § 230a** (Jean Lafitte NHP & Pres.) • **16 USC § 450kk** (Fort Union NM), • **16 USC § 459d-3** (Padre Island NS), • **16 USC § 459h-3** (Gulf Islands NS), • **16 USC § 460ee** (Big South Fork NRRA), • **16 USC § 460cc-2(i)** (Gateway NRA), • **16 USC § 460m** (Ozark NSR), • **16 USC § 698c** (Big Thicket N Pres.), • **16 USC § 698f** (Big Cypress N Pres.)	**36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart B** requires the owners/operators of nonfederally owned oil and gas rights outside of Alaska to • demonstrate bona fide title to mineral rights; • submit an Operations Permit Application to NPS describing where, when, how they intend to conduct operations; • prepare/submit a reclamation plan; and • submit a bond to cover reclamation and potential liability. **43 CFR Part 36** governs access to nonfederal oil and gas rights located in, or adjacent to, National Park System units in Alaska.	**Section 8.7.3** requires operators to comply with 9B regulations.

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

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Nonfederal minerals other than oil and gas	**NPS Organic Act, 54 USC §§ 100101 and 100751**	NPS regulations at **36 CFR Parts 1, 5, and 6** require the owners/operators of other types of mineral rights to obtain a special use permit from the NPS as a **§ 5.3** business operation, and **§ 5.7 – Construction of buildings or other facilities**, and to comply with the solid waste regulations at **Part 6**.	**Section 8.7.3** states that operators exercising rights in a park unit must comply with **36 CFR Parts 1 and 5**.
Coal	**Surface Mining Control and Reclamation Act of 1977, 30 USC § 1201 et. seq.** prohibits surface coal mining operations on any lands within the boundaries of a NPS unit, subject to valid existing rights.	**SMCRA Regulations at 30 CFR Chapter VII** govern surface mining operations on Federal lands and Indian lands by requiring permits, bonding, insurance, reclamation, and employee protection. **Part 7** of the regulations states that National Park System lands are unsuitable for surface mining.	None applicable.
Uranium	**Atomic Energy Act of 1954** Allows Secretary of Energy to issue leases or permits for uranium on BLM lands; may issue leases or permits in NPS areas only if president declares a national emergency.	None applicable.	None applicable.
Common Variety Mineral Materials (Sand, Gravel, Pumice, etc.)	**Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units. **Reclamation Act of 1939, 43 USC §387**, authorizes removal of common variety mineral materials from federal lands in federal reclamation projects. This act is cited in the enabling statutes for Glen Canyon and Whiskeytown National Recreation Areas, which provide that the Secretary of the Interior may permit the removal of federally owned nonleasable minerals such as sand, gravel, and building materials from the NRAs under appropriate regulations. Because regulations have not yet been promulgated, the National Park Service may not permit removal of these materials from these National Recreation Areas. **16 USC §90c-1(b)** authorizes sand, rock and gravel to be available for sale to the residents of Stehekin from the non-wilderness portion of Lake Chelan National Recreation Area, for local use as long as the sale and disposal does not have significant adverse effects on the administration of the national recreation area.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: • only for park administrative uses; • after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment; • after finding the use is park's most reasonable alternative based on environment and economics; • parks should use existing pits and create new pits only in accordance with park-wide borrow management plan; • spoil areas must comply with Part 6 standards; and • NPS must evaluate use of external quarries. Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Coastal Features and Processes	**NPS Organic Act, 54 USC § 100751 et. seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). **Coastal Zone Management Act, 16 USC § 1451 et. seq**. requires Federal agencies to prepare a consistency determination for every Federal agency activity in or outside of the coastal zone that affects land or water use of the coastal zone. **Clean Water Act, 33 USC § 1342/ Rivers and Harbors Act, 33 USC 403** require that dredge and fill actions comply with a Corps of Engineers Section 404 permit. **Executive Order 13089** (coral reefs) (1998) calls for reduction of impacts to coral reefs. **Executive Order 13158** (marine protected areas) (2000) requires every federal agency, to the extent permitted by law and the maximum extent practicable, to avoid harming marine protected areas. *See also "Climate Change"*	**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. *See also "Climate Change"*	**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 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 13693** (Planning for Federal Sustainability in the Next Decade) (2015) established to maintain Federal leadership in sustainability and greenhouse gas emission reductions.	*No applicable regulations, although the following NPS guidance should be considered:* **Coastal Adaptation Strategies Handbook (Beavers et al. 2016)** provides strategies and decision-making frameworks to support adaptation of natural and cultural resources to climate change. **Climate Change Facility Adaptation Planning and Implementation Framework**: The NPS Sustainable Operations and Climate Change Branch is developing a plan to incorporate vulnerability to climate change (Beavers et al. 2016b). **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. *Continued in 2006 Management Policies column*	**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. (2016). *NPS guidance, continued:* **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.

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. *2006 Management Policies, continued:* **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.	**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. ***continued in Regulations column***

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).

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U.S. Department of the Interior

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