National Park Service
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Natural Resource Stewardship and Science

Cabrillo National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2018/1666

ON THE COVER
Photograph of the tidepool area of the monument. The Old Point Loma Lighthouse overlooks the tidepools from its perch atop a marine terrace (Linda Vista terrace). The Point Loma Formation—70-million-year-old interbedded sandstone and siltstone—makes up the layered sea cliffs. The Point Loma Formation and undivided rocks of the Rosario Group compose the substrate of the tidepools. Red algal turf covers the substrate. NPS photograph (Geologic Resources Division).
THIS PAGE
Photograph of wave activity at the monument. Waves attack the monument's bedrock (Point Loma Formation). Old paralic deposits overlie the formation. They accumulated atop a wave-cut platform about 120,000 years ago, which has since been uplifted above sea level. The surface on which the visitors are walking is the Nestor terrace, which is composed of a wave-cut platform and overlying paralic deposits. NPS photograph (Cabrillo National Monument).

Cabrillo National Monument

Geologic Resources Inventory Report

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Katie KellerLynn

Colorado State University Research Associate
National Park Service Geologic Resources Inventory
Geologic Resources Inventory
PO Box 25287
Denver, CO 80225

June 2018
U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

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Please cite this publication as:

KellerLynn, K. 2018. Cabrillo National Monument: Geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2018/1666. National Park Service, Fort Collins, Colorado.

NPS 342/146245, June 2018

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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 of the NPS Natural Resource Stewardship and Science Directorate administers the GRI.

This report synthesizes discussions from a scoping meeting held in 2008 and a follow-up conference call in 2016 (see Appendix A). Chapters of this report discuss the monument's geologic setting, distinctive geologic features and processes within the monument, geologic issues facing resource managers, the geologic history leading to the present-day landscape, and information about the previously completed GRI map data. A poster (in pocket) illustrates these data.

This GRI report was written for resource managers at Cabrillo National Monument to support science-informed decision making. It may also be useful for interpretation. This report is accompanied by three GRI GIS data sets: (1) cabr_geology.mxd was compiled from a 1:100,000-scale source map by Kennedy and Tan (2008). That data set includes both "onshore" and "offshore" geology. (2) polm_geology.mxd was compiled from a 1:24,000-scale source map by Kennedy (1975). It shows the geology of the Point Loma quadrangle; it does not include offshore geology. (3) plhz_geology.mxd was compiled from a 1:24,000-scale source map by Tan (1995); it shows landslide susceptibility and landslide distribution on the Point Loma peninsula.

The report was prepared using available geologic information, including the aforementioned source maps by the California Geological Survey. The NPS Geologic Resources Division conducted no new fieldwork in association with the preparation of this report.

Resource managers may find *Geological Monitoring* (Young and Norby 2009) useful for addressing geologic resource management issues discussed in this report. 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 management, suggested methods of monitoring, and case studies.

The monument is located 8 km (5 mi) southwest of downtown San Diego, California, and was established in 1913 to memorialize Juan Rodriguez Cabrillo and his 1542 voyage of exploration. The monument was initially administered by the US War Department; it was transferred to the National Park Service in 1933. The monument is at the southern end of Point Loma, which is a north–south-oriented peninsula that separates San Diego Bay on the east from the Pacific Ocean to the west. In addition to the National Park Service, four other land holders—listed alphabetically, the City of San Diego (Point Loma Wastewater Treatment Plant), US Coast Guard (Point Loma Light Station), US Department of Veterans Affairs (Fort Rosecrans), and US Navy (Naval Base Point Loma)—share responsibility of protecting and restoring Point Loma as part of the Point Loma Ecological Conservation Area (PLECA).

The monument contains rare natural and cultural resources. The historic lighthouse rests on very old paralic (shoreface) deposits that accumulated atop a wave-cut platform about 855,000 years ago. During the Quaternary Period (the last 2.6 million years), regional uplift associated with the Rose Canyon fault zone raised the platform and associated sediments, which together constitute one of three marine terraces at the monument; the other two terrace levels are younger and lower in elevation but still above the present-day shoreline. These young marine terraces are much less lithified than the monument's bedrock and thus form hillslopes rather than cliffs.

Upper Cretaceous (100 million–66 million years ago) rocks make up the monument's bedrock. Sand, silt, and cobble that compose these rocks were deposited in a huge submarine fan that spread onto the floor of the Pacific Ocean into water as much as 1,000 m (3,300 ft) deep. Sediment in the fan came from the ancestral Peninsular Ranges to the east and was transported by west-flowing rivers to the shoreline then by sediment gravity flows down the submarine fan. Subsequent tectonic deformation associated with faulting has uplifted these rocks above sea level, where they now form the substrate of the monument.

Geologic features and processes identified during the 2008 GRI scoping meeting and 2016 follow–up conference call include the following:

- **Paleogeographic Setting**. Between 76 million and 72 million years ago, a huge submarine fan was deposited by sediment gravity flows (avalanches of sand and mud) onto the floor of the Pacific Ocean as the oceanic Farallon plate subducted beneath the western margin of the continental North American plate. The source of this sediment was a magmatic arc (arcuate line of plutons, volcanic rocks, or active volcanoes) represented by the Peninsular Ranges that formed on the overriding continental plate. Sediment eroded from the rising magmatic arc and flowed into a forearc basin (seaward of the magmatic arc), creating a submarine canyon and fan system that extended from the shoreline across the continental shelf and onto the basin plain. The bedrock at the monument represents this submarine fan system.
- **Cretaceous Rocks and Fossils**. The monument's bedrock consists of the undivided rocks of the Rosario Group in the offshore area (map unit **Kuo**), the Point Loma Formation (**Kp**), and the Cabrillo Formation (**Kcs** and **Kccg**); these rocks are from the Late Cretaceous ("**K**") Period. The Rosario Group is subdivided into three formations: (1) Lusardi, (2) Point Loma, and (3) Cabrillo. Onshore bedrock in the monument consists of the Point Loma and Cabrillo Formations. Offshore bedrock consists of the undivided Rosario Group. Rocks assigned specifically to the Lusardi Formation, the basal unit of the Rosario Group, do not occur in the monument.
- **Offshore Geology**. In addition to the undivided rocks of the Rosario Group in the offshore area (**Kuo**), which occur on the western side of the monument, undivided marine deposits in offshore region (**Qmo**) were mapped just beyond the eastern boundary of the monument. These map units occur below the Pacific Ocean and San Diego Bay. Rarely do geologic maps show what lies below the surface of large bodies of water, so the GRI GIS data for the monument are an exceptional source of information. The uncommon availability of offshore geologic mapping is one reason that the entire San Diego 30' × 60' quadrangle (Kennedy and Tan 2008, scale 1:100,000) was included in the GRI GIS project.
- **Faults**. Much of coastal San Diego lies astride the Rose Canyon fault zone, which is characterized by right-lateral strike-slip movement, where the sense of motion along the fault is horizontal with the opposite block across the fault plane moving to the right. Individual strands within the fault zone, however, display various combinations of dip slip (vertical) and strike slip (horizontal) motion. San Diego owes much of its aesthetic beauty to these changes in relative motion, which have resulted in the uplift of Point Loma and the downwarping of San Diego Bay.
- **Marine Terraces**. A series of continually evolving marine platforms were carved by wave action, covered with paralic deposits (e.g., nearshore marine, beach, estuarine, lagoon, and continental dune), and uplifted during the Quaternary ("**Q**") Period. Kennedy and Tan (2008, plate 2) provided an uplift rate of 13 cm (5 in) per 1,000 years. Marine terraces record a history of both tectonic uplift and fluctuations in sea level. In the monument, Kennedy and Tan (2008) mapped the deposits associated with these platforms—commonly referred to as "wave-cut platforms" though Kennedy and Tan (2008) referred to them as "abrasion platforms"—as paralic deposits, from oldest to youngest, (1) very old paralic deposits, undivided (**Qvop**); (2) old paralic deposits, Unit 6 (**Qop6**); and (3) old paralic deposits, Unit 7 (**Qop7**). The paralic deposits in the monument can be correlated with a series of 21 marine terraces in the San Diego area. Very old paralic deposits, undivided (**Qvop**) are associated with the Linda Vista terrace (approximately 855,000 years old). Old paralic deposits, Unit 6 (**Qop6**) are associated with the Nestor terrace (approximately 120,000 years old). Old paralic deposits, Unit 7 (**Qop7**) are associated with the Bird Rock terrace (approximately 80,000 years old). Ages of marine terraces used in this report are from Kennedy and Tan (2008, plate 2), which were based on uranium series dating of invertebrate fossils (corals) in sediments on the abrasion platforms.
- **Sea Cliffs, Sea Caves, and Other Coastal Features**. Around Point Loma, erosion has led to an irregular shoreline, consisting of vertical or nearly vertical sea cliffs punctuated by surge channels (linear waterways in rock where breaking waves cause inflow and outflow of water), sea caves, blowholes (nearly vertical holes in the roof of a sea cave), coves, and an occasional sea stack, arch, or pillar. Also, a few pocket beaches occur at the base of the cliffs. Sea cliffs in the monument are composed of the Point Loma and Cabrillo Formations. On the eastern side of the monument, the Cabrillo Formation dominates the cliffs. On the western side of the monument, the Point Loma Formation prevails. Notable sea caves have formed at the base of the cliffs on the western side of the monument. Paralic deposits, mostly **Qop6** but some **Qop7** near the parking lot at the tidepool area, form the upper part of the cliffs at the monument.
- **Tidepools**. The monument's tidepools (pools of water left by an ebbing tide in rock basins) host

among the largest and most diverse habitats in San Diego County. The diversity and unusual character of life in the monument's tidepools are popular draws for visitor exploration. The rock basins have formed where uneven erosion has left depressions and clefts in the bedrock—Point Loma Formation (**Kp**) onshore and the undivided rocks of the Rosario Group (**Kuo**) offshore.

- **Aeolian Features and Processes**. Aeolian (windblown) features on Point Loma develop primarily as long, linear beach ridges against old sea cliffs and at the fore edge of marine terraces. At scale 1:100,000, Kennedy and Tan (2008) did not map any aeolian deposits in the monument, but scoping participants identified some small-scale aeolian features, including windblown sand and dunes in the intertidal zone (tidepools) and on the bayside of the monument.
- **Old Point Loma Lighthouse**. Identifying the building stone of significant cultural features, such as the Old Point Loma Lighthouse, is of interest for the Geologic Resources Inventory. The building stone used in construction of the lighthouse is sandstone from either the Point Loma or Cabrillo formations, but its source is not well documented and further investigation is needed to make an accurate connection between this particular cultural and associated geologic resources.

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

- **Climate Change Planning**. The potential consequences of rapid climate change overshadow all other concerns for the natural resources at the monument. Sea level rise is a primary concern. Higher sea levels have the potential to change ocean–land access points, which are economically important for the ports in San Diego Bay. In addition, sea level rise will impact the ecologically significant intertidal zone (tidepools). Climate change impacts such as sea level rise, increased hurricane strength, and increased wave height also will affect monument infrastructure, including buildings and parking lots, though non-NPS structures directly north and south of the monument are at greater risk. The National Park Service has developed a variety of databases and publications that provide guidance for managing coastal resources and planning for the impacts of climate change.
- **Sea Cliff Erosion**. Much of the cliff erosion at the monument is a result of the growth and collapse of sea caves. The primary area of concern related to sea cliff erosion at the monument is where potential collapse of a sea cave in the monument is threatening the road to the Point Loma Wastewater Treatment Plant (north of the monument). Determining the rate of cliff erosion at this location would be valuable for resource management and park planning. Studies conducted along the Point Loma sea cliffs, in particular on the western side of the peninsula at Sunset Cliffs (north of the monument), have yielded average rates of sea cliff erosion ranging from 1.3 cm (0.5 in) per year over 75 years to 160 cm (63 in) per year over 65 years. This large range is a result of differences in the quality of the data analyzed, time period evaluated, and the section of cliff studied. Less is known about rates of erosion on the eastern side of the monument, which is susceptible to landslides. Monument managers are encouraged to contact the Geologic Resources Division for technical assistance with sea cliff erosion.
- **Cave Resource Management**. All of the caves in the monument are sea caves, which formed at the base of sea cliffs. A park-specific cave management plan has not been conducted at the monument. Cave management plans include a comprehensive evaluation of current and potential visitor use and activities and outline the means to study known and discover new caves. The NPS Geologic Resources Division can facilitate the development of a cave management plan for the monument.
- **Slope Hazards**. A relative landslide susceptibility and distribution map by Tan (1995) is included in the GRI GIS data. The eastern half of the monument is considered "most susceptible" to landslides. The tidepool area on the western side of the monument is considered "most susceptible" to cliff failures. The Bayside Trail is a primary area of concern. The trail cuts across the eastern side of the monument, which is characterized by unstable slopes underlain by weak materials and/or affected by folding and faulting of strata. Two large landslides destroyed sections of the trail in 2005. The Geological Monitoring chapter about slope movements (Wieczorek and Snyder 2009) provides guidance for monitoring slope hazards.
- **Earthquakes**. Earthquakes can directly damage park infrastructure or trigger other hazards, such as landslides and cliff failures, which may impact park resources, infrastructure, or visitor safety. The Rose Canyon fault zone poses the primary seismic hazard to the San Diego area. The last moderately large earthquake to strike San Diego took place on 27 May 1862 and measured an estimated magnitude (M) 5.9. Such an earthquake has a 0.20–0.25 probability (20%–25% "chance") of occurring in the vicinity of the monument in the next 50 years. Earthquakes along the Rose Canyon fault zone have a maximum estimated magnitude of 6.9; such an earthquake

has a 0.04–0.06 probability (4%–6% "chance") of occurring in the vicinity of the monument in the next 50 years. Hazards associated with a moderately large earthquake (M 5.0 or greater) in the San Diego area include fault rupture, shaking, liquefaction, landslides, and tsunami.

- **Monitoring the Physical Environment of Tidepools**. To date, monitoring at the monument has focused on key intertidal species, bird and visitor counts (i.e., few birds are found in the presence of many people while large numbers of birds are only found in the absence of large crowds), and human visitation. In the event that monument managers choose to monitor the physical environment of tidepools, the Geological Monitoring chapter about marine features and processes (Bush 2009) may be of interest.
- **Paleontological Resource Inventory, Monitoring, and Protection**. The monument's bedrock and paralic deposits contain fossils. Three NPS publications documented fossils at the monument: Koch and Santucci (2003), Tweet et al. (2012), and Tweet et al. (2014). A park-specific, field-based, paleontological inventory has not been conducted in the monument. Such an inventory could provide detailed, site-specific descriptions and resource management recommendations. Many fossils can be seen along the coast and in the tidepools at the monument. Constant coastal erosion can rapidly expose and destroy these fossils, presenting challenges to their management and protection. Monument managers may find the Geological Monitoring chapter about in situ paleontological resources (Santucci et al. 2009) useful for management.
- **Dredging**. The Unified Port of San Diego (a public benefit corporation and special government entity) maintains a central navigation channel in San Diego Bay by dredging. Dredged material may be used for beach replenishment at Imperial Beach; dumped into the Pacific Ocean at the US Army Corps of Engineers ocean disposal site LA-5, which is about 6 km (4 mi) from the western shore of Point Loma; or relocated within San Diego Bay to serve as artificial reefs. Dredging is a geologic resource management issue because creating and maintaining a navigation channel can affect the stability of adjacent shorelines, sediment transport, water turbidity, and currents. In addition, ecological impacts may occur in areas where sand is dredged and placed. Dredging may also affect water quality. Various NPS publications provide guidance for managers in parks where dredging is an issue. Resource managers at the monument are encouraged to contact the NPS Geologic Resources Division for technical assistance.

Products and Acknowledgments

The NPS Geologic Resources Division partners with the Colorado State University Department of Geosciences to produce GRI products. The US Geological Survey, state geological surveys, local museums, and/or universities developed the source maps and reviewed GRI content. This chapter describes GRI products and acknowledges contributors to this report.

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 nongeoscientists.

Scoping meetings bring together park staff and geologic experts to review and assess available geologic maps, develop a geologic mapping plan, and discuss geologic features, processes, and resource management issues that should be addressed in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to 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. 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.

Acknowledgments

The GRI team thanks the participants of the 2008 scoping meeting and 2016 conference call (see Appendix A) for their assistance in this inventory. Thanks very much to the California Geological Survey for its maps of the area; this report and accompanying GIS data could not have been completed without them. Thanks to Trista Thornberry-Ehrlich (Colorado State University) for her help in creating many of the graphics in this report. Thanks to Keith Lombardo (Cabrillo National Monument) for his review of this report, general assistance and answering of questions, and for providing and/or getting permission to use many of the photographs in this report. Thanks to Zane Jobe (Colorado School of Mines) for his general review and specifically for his suggestions about how to update the discussion of submarine fans. Thanks to Courtney Schupp (NPS Geologic Resources Division) for her thorough review of all-things-coastal and related to climate change.

Review

Marsha Davis (NPS Pacific West Regional Office)
Zane Jobe (Colorado School of Mines)
Jason Kenworthy (NPS Geologic Resources Division)
Keith Lombardo (Cabrillo National Monument)
Vincent Santucci (NPS Geologic Resources Division)
Courtney Schupp (NPS Geologic Resources Division)
Matthew Thomas (US Geological Survey)
Justin Tweet (NPS Geologic Resources Division)

Editing

Michael Barthelmes (NPS Geologic Resources Division)

Report Formatting and Distribution

Jason Kenworthy (NPS Geologic Resources Division)

Source Maps

Michael P. Kennedy (California Geological Survey)
Siang S. Tan (California Geological Survey)

GRI GIS Data Production

Ron Karpilo (Colorado State University)
Stephanie O'Meara (Colorado State University)
Dave Green (Colorado State University)

GRI Map Poster Design

Georgia Hybels (Colorado State University)

GRI Map Poster Editing

Georgia Hybels (Colorado State University)
Rebecca Port (NPS Geologic Resources Division)
Michael Barthelmes (NPS Geologic Resources Division)
Jason Kenworthy (NPS Geologic Resources Division)

Figure 1. Area map. Cabrillo National Monument is situated on the Point Loma peninsula near San Diego, California. The peninsula forms the western side and entrance to San Diego Bay. The Pacific Ocean is on the west. Graphic by Trista Thornberry-Ehrlich (Colorado State University) using ESRI World Imagery basemap.

Geologic Setting and Significance

This chapter describes the regional geologic setting of the monument and summarizes connections among geologic resources, other park resources, and park stories.

Cabrillo National Monument celebrates the spirit of discovery and protects rare natural and cultural resources on the Point Loma peninsula. Located near San Diego, California, the naturally beautiful peninsula is 4.0-km- (2.5-mi-) long and rises 129 m (422 ft) above sea level. It is surrounded by the Pacific Ocean and San Diego Bay (fig. 1). Cabrillo National Monument is at the southern end of the peninsula and incorporates the highest point. The monument consists of 65 onshore hectares (160 ac) and 49 offshore hectares (120 ac). According to Curdts (2011), the monument includes 2.4 shoreline kilometers (1.5 mi).

The monument boasts one of the best harbor views in the world. On clear days, scenic panoramas stretch from Mexico to the snow-capped mountains east of Los Angeles. These expansive views are a primary visitor attraction, with the best viewing opportunities near the Old Point Loma Lighthouse. Historically, Point Loma has been used for observation of the Pacific Ocean and San Diego Bay, serving strategic military, navigational, and recreational purposes (National Park Service 2016b).

The Old Point Loma Lighthouse serves as the monument's cultural centerpiece and has become the landmark symbol of the City of San Diego (National Park Service 1993). The Old Point Loma Lighthouse is located at the highest point of the peninsula and rests on very old paralic (shoreface) deposits (map unit **Qvop**). During the Quaternary Period (fig. 2, p. 2), marine terraces (uplifted, abandoned strips of coastline) developed on platforms that were cut into the bedrock between 855,000 and 80,000 years ago. Pleistocene paralic deposits (**Qvop**, **Qop6**, and **Qop7**) rest upon these wave-cut platforms. The combination of wave-cut platform and overlying deposits constitutes a terrace.

The Old Point Loma Lighthouse is partly constructed of local sandstone of either the Cabrillo (**Kcs**) or Point Loma (**Kp**) Formations. The lighthouse stood watch over the entrance of San Diego Bay for 36 years (1855–1891). What seemed to be a good location had a serious flaw, however; fog and low clouds often obscured the light (fig. 3). Thus a new lighthouse location was established closer to the water and began operation in 1891. Today, the Point Loma Light Station at the tip of the peninsula is operated by the US Coast Guard (fig. 4).

In addition to the National Park Service and US Coast Guard, three other land holders—(1) the US Navy at Naval Base Point Loma, (2) the US Department of Veterans Affairs at Fort Rosecrans, and (3) the City of San Diego at the Point Loma Wastewater Treatment Plant—share ownership and management of the Point Loma peninsula (fig. 5). In 1995, approximately 270 ha (668 ac) of Point Loma was designated as an ecological reserve—the Point Loma Ecological Conservation Area (PLECA)—to be protected and restored by these land holders.

Centuries of human activity in the region and ongoing urban development on the peninsula have made the remaining natural habitats at the monument among the rarest in the world (National Park Service 2014). The west side of the monument is home to a variety of marine and coastal habitats, including the rocky intertidal zone (area between high and low tide). This zone in the monument is commonly referred to as the tidepool area. Undivided rocks of the Rosario Group in the offshore area (**Kuo**) and the Point Loma Formation (**Kp**) make up the rocky intertidal zone and serve as the substrate that supports an impressive tidepool community (fig. 6). Also, just beyond the monument's offshore boundary, undivided rocks of the Rosario Group are the substrate for "kelp forests" where large marine plants known as kelp form tall, underwater "trees." The kelp forests help support life in the deeper ocean (National Park Service 2015c).

The monument is known for its on-land opportunities to view marine life and is a popular whale-watching location. During the annual migration, from December through February, Pacific gray whales (*Eschrichtius robustus*) pass by the monument. The monument is also an important stopover for birds along the Pacific Flyway (National Park Service 2015d).

The monument has a Mediterranean climate characterized by cool, mild winters and warm, dry summers. Weather data are recorded for San Diego at Lindbergh Field (the airport), which is directly across the bay from the monument. The average annual temperature is 18°C (64°F). The average annual rainfall is a scant 24 cm (9 in). Rainfall is concentrated in the winter, from November to April, but the amount can vary drastically from year to year. This variability causes certain types of plants to thrive one year and barely survive another. This lack of rain is made up for when cold air from the ocean meets the balmy air on the land and dense fogs rolls in. Fog adds moisture, allowing species requiring more water to coexist with plants

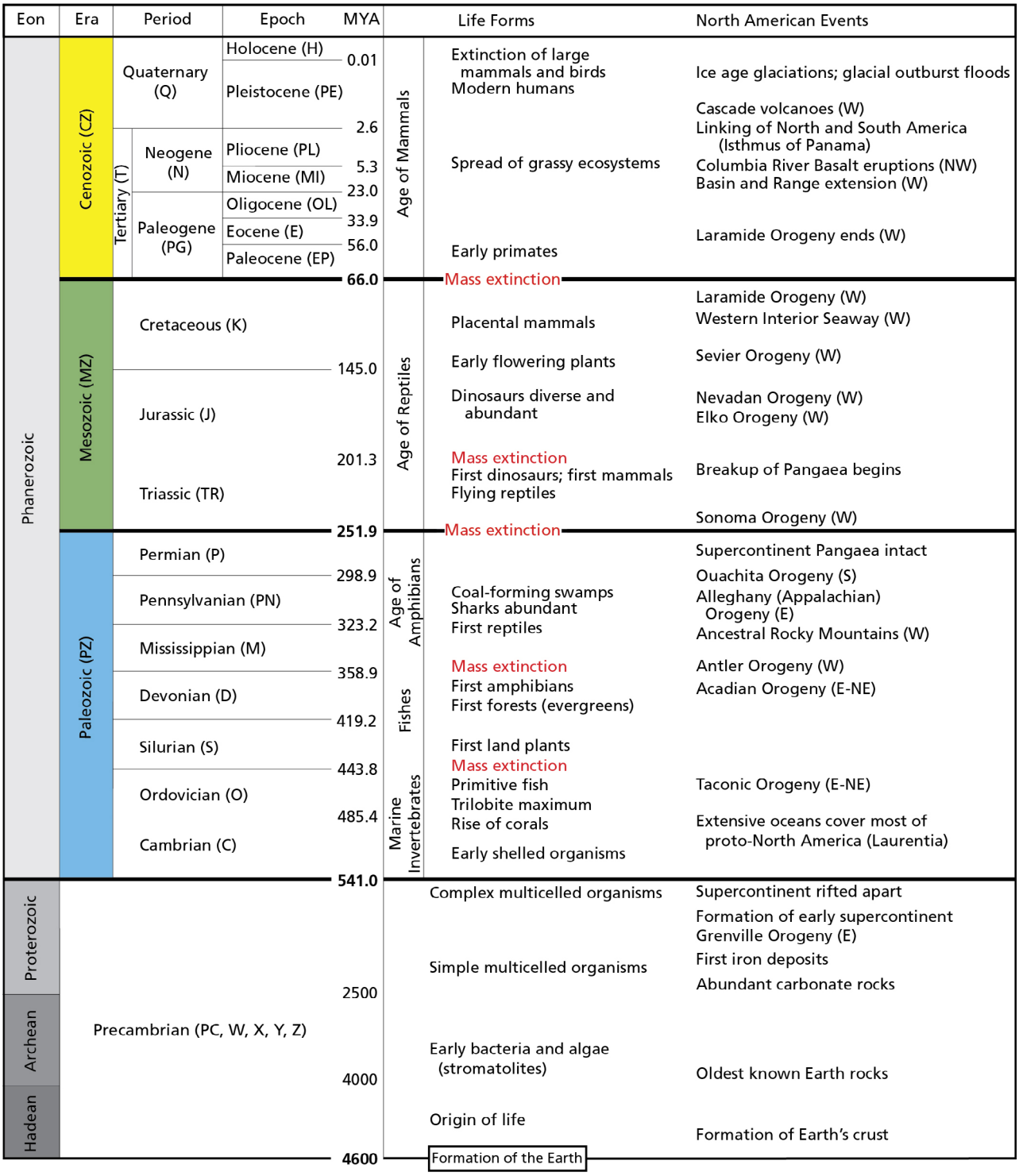


Figure 2. Geologic time scale.
The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. The vertical spacing of the time scale does not represent the amount of time in each era; please refer to the boundary ages, which are in millions of years ago (MYA). The Precambrian accounts for more than 85% of geologic time. GRI map abbreviations for each time division are in parentheses. Compass directions in parentheses indicate the regional locations of events. Bedrock units in the monument are from the Late Cretaceous (K) Period. Surficial units are from the Quaternary (Q) Period. National Park Service graphic using dates from the International Commission on Stratigraphy (2017).

Figure 3. Photograph of Old Point Loma Lighthouse.
Repeatedly shrouded in fog, the Old Point Loma Lighthouse was ultimately decommissioned, and the "new" light station at the tip of the peninsula began operation in 1891. The Old Point Loma Lighthouse was used for 36 years. It remains as the cultural centerpiece of the monument. NPS photograph available at http://www.nps.gov/cabr/learn/photosmultimedia/photogallery.htm (accessed 20 July 2017).

Figure 4. Aerial photograph of Point Loma.
The Old Point Loma Lighthouse is maintained by the National Park Service. The Point Loma Light Station is operated by the US Coast Guard. Note the spectacular outcrop (type section) of the Cabrillo Formation in the cliff face to the east (right) of the light station; the Point Loma Formation crops out in the underlying cliffs at sea level. The Point Loma type section consists of the cliffs that line the western side of the Point Loma peninsula. The Point Loma Wastewater Treatment Plant (north of the monument boundary) is managed by the City of San Diego. California Coastal Records Project, Image 200805013, taken 19 September 2008. Copyright © 2002–2018 Kenneth & Gabrielle Adelman, California Coastal Records Project, http://www.californiacoastline.org.

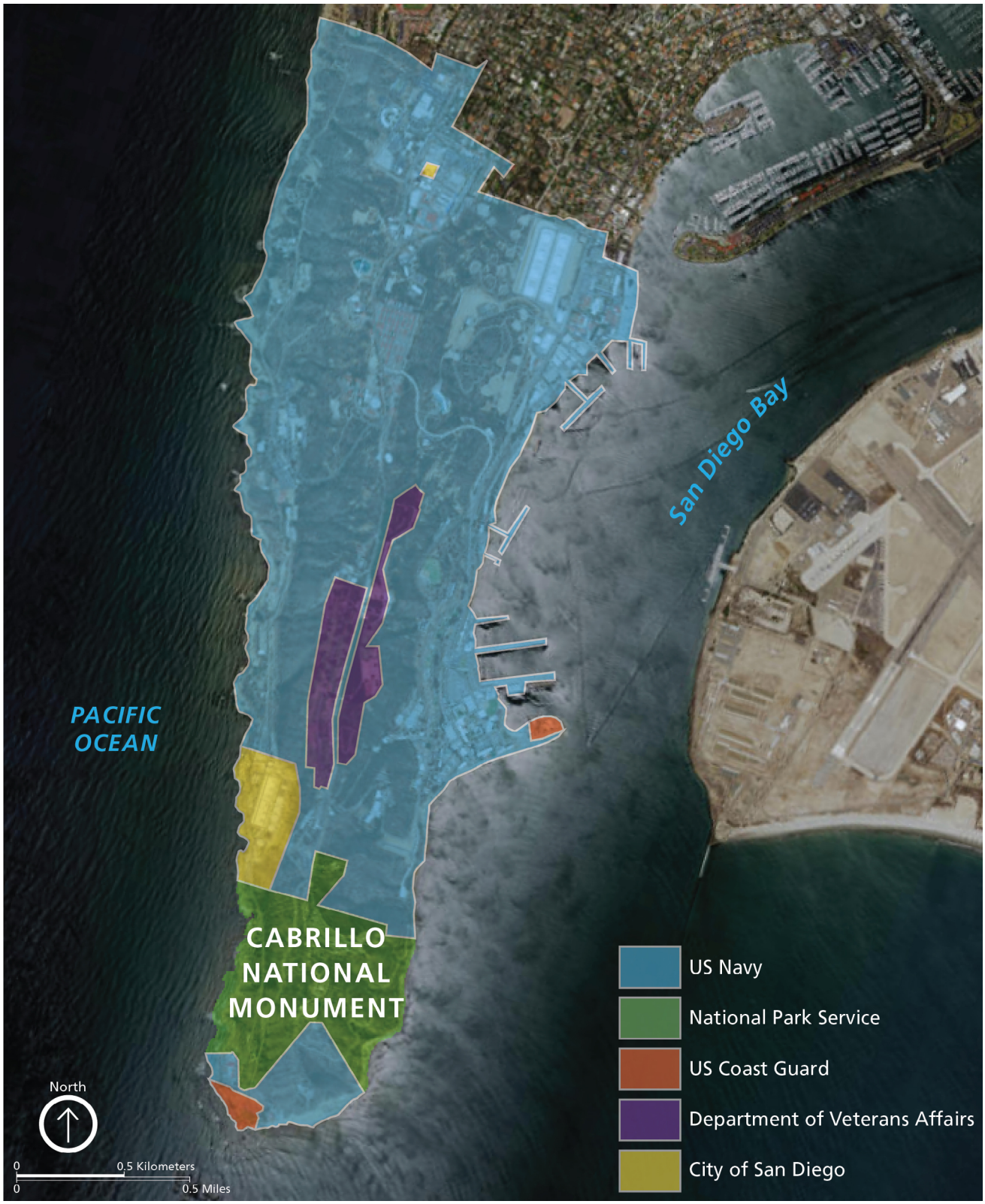


Figure 5. Map of jurisdictional boundaries on Point Loma.
Five land holders share ownership and management of the Point Loma peninsula: (1) the National Park Service at Cabrillo National Monument, (2) US Navy at Naval Base Point Loma, (3) US Coast Guard at Point Loma Light Station, (4) Department of Veterans Affairs at Fort Rosecrans, and (5) the City of San Diego at the Point Loma Wastewater Treatment Plant. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Naval Base Point Loma and Cabrillo National Monument (2006, map 1-2).

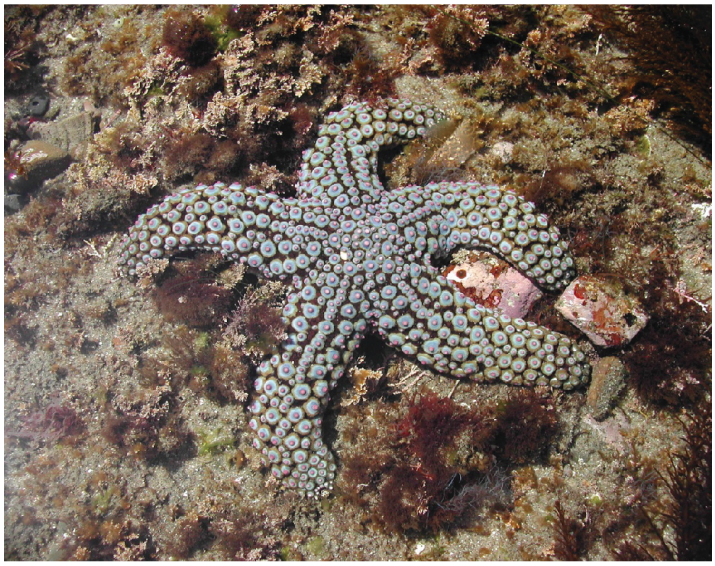


Figure 6 (left). Photographs of sea life. A diversity of lifeforms inhabits the tidepools at the monument, including, from top to bottom, bat star (*Patiria miniata*), sea anemone (*Anthopleura xanthogrammica*), and knobby sea star (*Pisaster giganteus*). The exact dimensions of these particular sea animals are unknown, but in general, sea anemones are less than 10 cm (4 in) across and sea stars are less than 15 cm (6 in) across. The tidepools (rock basins), which retain water left by an ebbing tide, are composed of the Point Loma Formation (Kp) and the undivided rocks of the Rosario Group (Kuo). NPS photographs available at http://www.nps.gov/cabr/learn/photosmultimedia/photogallery.htm (accessed 20 July 2017).

and animals typically associated with desert areas. The ocean also keeps air temperatures mild year-round, which enables heat-loving cacti to grow next to cool-seeking evergreen shrubs; mosses to grow in the shade near parched lichen clinging to dry, hot boulders; and water-bound salamanders to amble past sunning, dry-land snakes (National Park Service 2015a).

The monument was named for Juan Rodriguez Cabrillo, a Portuguese-born explorer who on 28 September 1542, in the service of the King of Spain, became the first European to sail into what is now known as San Diego Bay and set foot on what is now known as the West Coast of the United States. On 27 June 1542, Cabrillo sailed from Navidad, Mexico, and three months later arrived at "a closed and very good port" (National Park Service 2007), which he called "San Miguel" in honor of arriving on that saint's birthday. Sixty years later, Sebastian Vizcaino, another explorer, changed the name to "San Diego." Historians believe Cabrillo anchored his flagship *San Salvador* (fig. 7) near Point Loma's eastern shore. Cabrillo later died during the expedition, after suffering complications resulting from infection following a broken bone (one account says "arm," another says "leg"), which he broke on San Miguel Island in the Channel Islands north of the monument (see scoping summary about Channel Islands National Park by KellerLynn 2008b). His crew pushed on, possibly as far north as Oregon, before thrashing winter storms forced them back to Mexico (National Park Service 2015b).

Cabrillo's expedition resulted in the first written record (by a European) of North America's

Figure 7. Photograph of San Salvador replica.
The San Diego Maritime Museum, in partnership with Cabrillo National Monument, built a historically accurate replica of the Cabrillo's flagship San Salvador. The replica matches the original in size, weighing 150 tons and measuring 92 feet long by 24 feet wide. The Maritime Museum of San Diego and an estimated 500 volunteers built the replica at Spanish Landing in San Diego between 2011 and 2015. Point Loma is in the background. Photograph by Jerry Soto (Maritime Museum of San Diego) used by permission.

western coast. The expedition also helped dispel myths and misconceptions, such as the existence of a route to Asia and the Spice Islands and a passage (Strait of Anián) from the Pacific Ocean to the Atlantic Ocean. During the expedition, Cabrillo and his crew charted landmarks, winds, and currents, which allowed Cabrillo's contemporaries to proceed with colonizing the expanded Spanish Empire.

Nearly 400 years after Juan Rodriguez Cabrillo's historic arrival, President Woodrow Wilson memorialized the explorer by creating Cabrillo National Monument in 1913. Today, a heroic statue of Cabrillo looks out over San Diego Bay (fig. 8). Cabrillo National Monument was initially managed by the War Department. The National Park Service became its steward in 1933.

Long before Cabrillo sailed into San Diego Bay and President Wilson set aside the monument, the area's geologic story was building on the floor of the Pacific Ocean and in the developing Peninsular Ranges to the east. Between 76 million and 72 million years ago (Late Cretaceous Period; fig. 2), sediment shed from the Peninsular Ranges and transported through a submarine fan system would come to form the monument's bedrock, namely, the Point Loma (**Kp**) and Cabrillo (**Kcs** and **Kccg**) Formations. Kennedy and Moore (1971) formally named and described these formations from reference exposures, referred to as "type sections," in the sea cliffs in and near the monument (fig. 4). The place where a sequence of strata, such as a formation, is best exposed, and was commonly first described, is a type section. Type sections serve as objective standards with which spatially separated parts of a unit may be compared. Type sections are notable for the Geologic Resources Inventory, and the NPS Geologic Resources Division is developing a database of designated type sections in parks across the country. The US Geologic Names Lexicon ("Geolex") website, http://ngmdb.usgs.gov/

Figure 8. Photograph of Cabrillo statue.
At the monument, a heroic statue of the explorer Juan Rodriguez Cabrillo overlooks San Diego Bay. Photograph by Francisco Santos, licensed under CC BY-SA 3.0 via Wikimedia Commons, https://commons.wikimedia.org/wiki/File:2006.03.07.us.ca.SDcabrilho.jpg (accessed 20 July 2017).

Geolex/search, provides location information and nomenclatural summaries for rock formations.

The Point Loma and Cabrillo Formations are two of the three formations that comprise the Rosario Group. Undivided rocks of the Rosario Group in the offshore area (**Kuo**) lie beneath the Pacific Ocean on the west side of the monument. To the east, Holocene (less than 11,700 years old) undivided marine deposits in the offshore region (**Qmo**) make up the seafloor of the Pacific Ocean and San Diego Bay (see poster, in pocket).

Rarely do geologic maps show rocks, deposits, and structural features that lay hidden below large bodies of water, so the GRI GIS data that accompany this report are an exceptional source of information. The uncommon availability of offshore geologic mapping is the reason that the entire San Diego 30’ × 60’ quadrangle (Kennedy and Tan 2008, scale 1:100,000) was included in the GRI GIS project (Ron Karpilo, Colorado State University, research associate, email communication, 10 December 2016). The GRI GIS data for the monument represent one of only a few datasets completed for the GRI that include subaqueous geology. The dataset for Crater Lake National Park is another example (see GRI report by KellerLynn 2013).

Only in the past few years has technology advanced to the point where scientists can accurately and efficiently determine the shape of the seafloor over large areas and begin to map its geologic features (State of California 2012). The ability to map offshore geology is significant for improving ocean management in the face of climate change, predicting coastal erosion and tsunami hazards, understanding sediment transport and delivery, and identifying habitat for living marine resources.

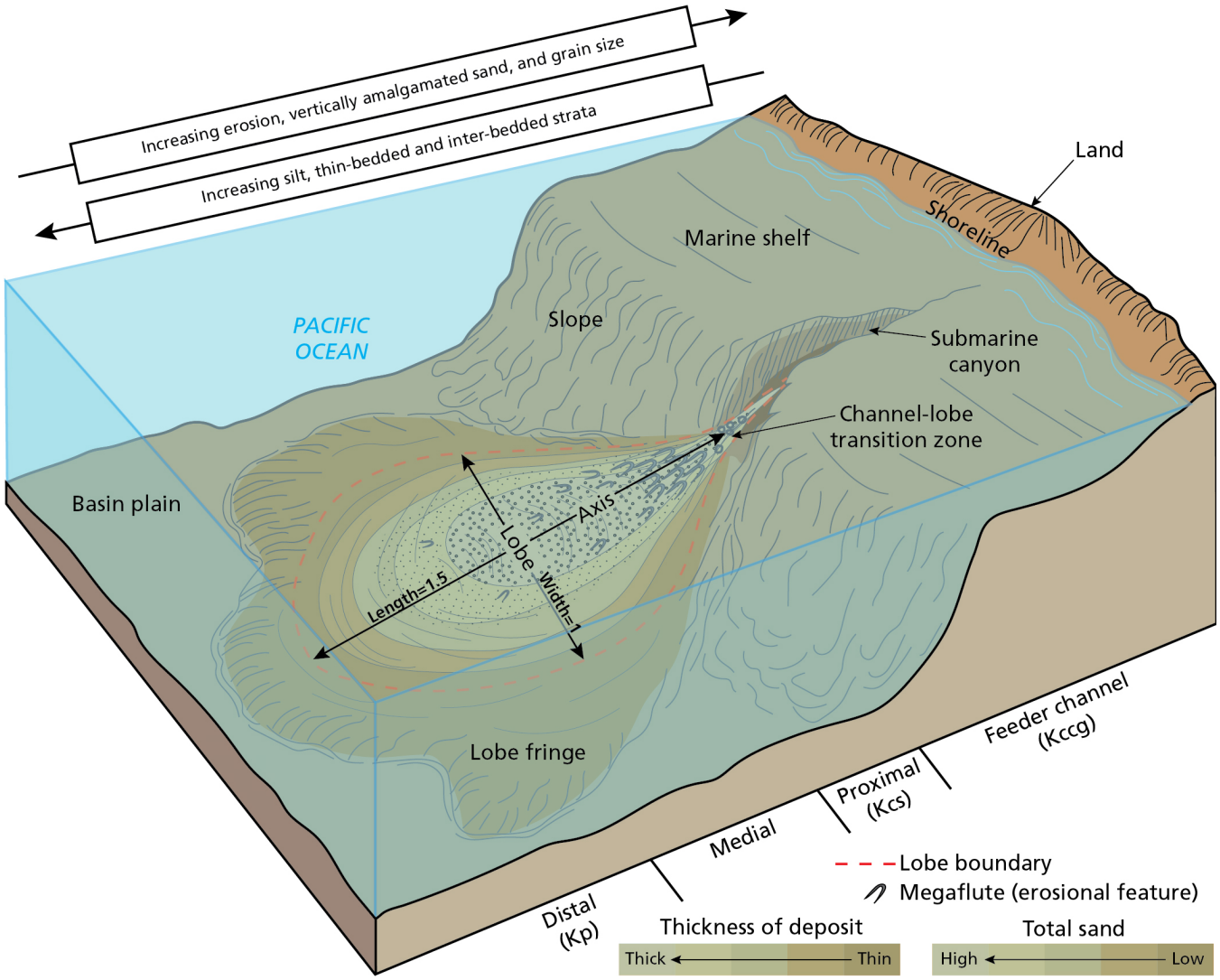


Figure 9. Graphic of submarine fan.
The onshore bedrock of the monument consists of sediments that were deposited in a huge submarine fan that was later uplifted above sea level. Four channel–lobe complexes comprise the entire fan system, which covered parts of the marine shelf, slope, and basin plain from what is now Point La Jolla to the tip of Point Loma. One generalized channel–lobe complex is shown in this figure. Fan complexes can be divided into the main feeder channel, as well as proximal, medial, and distal parts. The channel–lobe transition zone is marked by megaflutes (erosional features), which decrease down current. Within the monument, the fine-grained, interbedded sandstone and siltstone of the Point Loma Formation (Kp) represent the distal part of a lobe complex. The cobble conglomerate (Kccg) of the Cabrillo Formation represents a feeder channel. The medium-grained sandstone (Kcs) of the Cabrillo Formation represents the proximal part of a lobe complex. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Abbott and Rockwell (2004, p. 14) and Fleming (2010, figures 1.1, 4.1, and 4.9).

Geologic Features and Processes

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

Participants (see Appendix A) identified the following geologic features and processes at the monument during the 2008 scoping meeting (see scoping summary by KellerLynn 2008a) and 2016 conference call. In general, these features and processes are ordered by scale, with larger scale features discussed before smaller scale features.

- Paleogeographic Setting
- Cretaceous Rocks and Fossils
- Offshore Geology
- Faults
- Marine Terraces, Uplift, and Fossils
- Sea Cliffs, Sea Caves, and Other Coastal Features
- Tidepools
- Aeolian Features and Processes
- Old Point Loma Lighthouse

Paleogeographic Setting

Between 76 million and 72 million years ago (Late Cretaceous Period; fig. 2), the sediments that compose the monument's bedrock—Point Loma (**Kp**) and Cabrillo (**Kcs** and **Kccg**) Formations—were deposited in a huge submarine fan (Abbott and Rockwell 2004). Submarine fans form in much the same way as on-land alluvial fans. In both cases, a massive apron of sediment accumulates at the base of a steep slope. In the case of the submarine fan that became the Point Loma Formation, sediment was deposited at depths as much as 1,000 m (3,300 ft) below sea level (Nilsen and Abbott 1981). Submarine fans differ from alluvial fans in that the sediment-transport mechanism is predominantly sediment gravity flows (dense flows of sand and mud; see table 1) pulled downslope, with internal water carried along for the ride (Abbott 1999). These flows are comparable to a snow avalanche, but with sand and water rather than snow and air. By contrast, running water drives most of the downward transport of material in alluvial fans.

Submarine fans may be characterized as channel–lobe complexes (see Deptuck et al. 2008; Prélat et al. 2009, 2010; Fleming 2010). In a channel–lobe complex, large amounts of sand accumulate at the termination of a main feeder channel, which may be a short-lived gully or a long-lived submarine canyon, as in the case of Point Loma. Accumulated sand normally forms a convex-upward, lens-shaped (in cross section) and lobate (in plan view) deposit, referred to as a "lobe" (fig. 9). Most of the sand in a lobe accumulates along a thick axis, thinning toward the distal margin. Grain size decreases away from the lobe axis, as well as from the feeder channel such that finer sediments are deposited farther offshore in deeper water. Larger clasts (fragments of a rock that came from a larger rock mass) such as cobbles remain in the channel whereas smaller clasts such as silt are transported down-current in suspension. In a transition zone between the feeder channel and the lobe, "megaflutes" (erosional features) may form; the abundance of these features decreases downslope (fig. 9, facing page).

A series of lobe complexes composes a larger submarine fan system (fig. 10). Four, stacked lobe complexes make up the system that became the Point Loma Formation (Fleming 2010). The Point Loma Formation in the monument is a fine-grained sandstone and siltstone that was deposited in the distal part of a lobe complex (Fleming 2010). Most of the sand and silt was deposited along the lobe axis by turbidity currents (avalanches

Table 1. Clastic sedimentary rock classification and characteristics.
Note: With a clast size of less than1/256 mm (0.00015 in), claystone is smaller than siltstone. As mapped by Kennedy and Tan (2008), none of the formations in the monument consist of claystone. Claystones and siltstones can also be called "mudstone," or if they break into thin layers, "shale."

Rock Name	Clast Size	Associated Rock Formations at Cabrillo National Monument
Conglomerate (rounded clasts) or breccia (angular clasts)	greater than 2 mm (0.08 in)	Cabrillo Formation (**Kccg**) Rosario Group (**Kuo**)
Sandstone	1/16–2 mm (0.0025–0.08 in)	Cabrillo Formation (**Kcs**) Point Loma Formation (**Kp**) Rosario Group (**Kuo**)
Siltstone	1/256–1/16 mm (0.00015–0.0025 in)	Point Loma Formation (**Kp**) Rosario Group (**Kuo**)

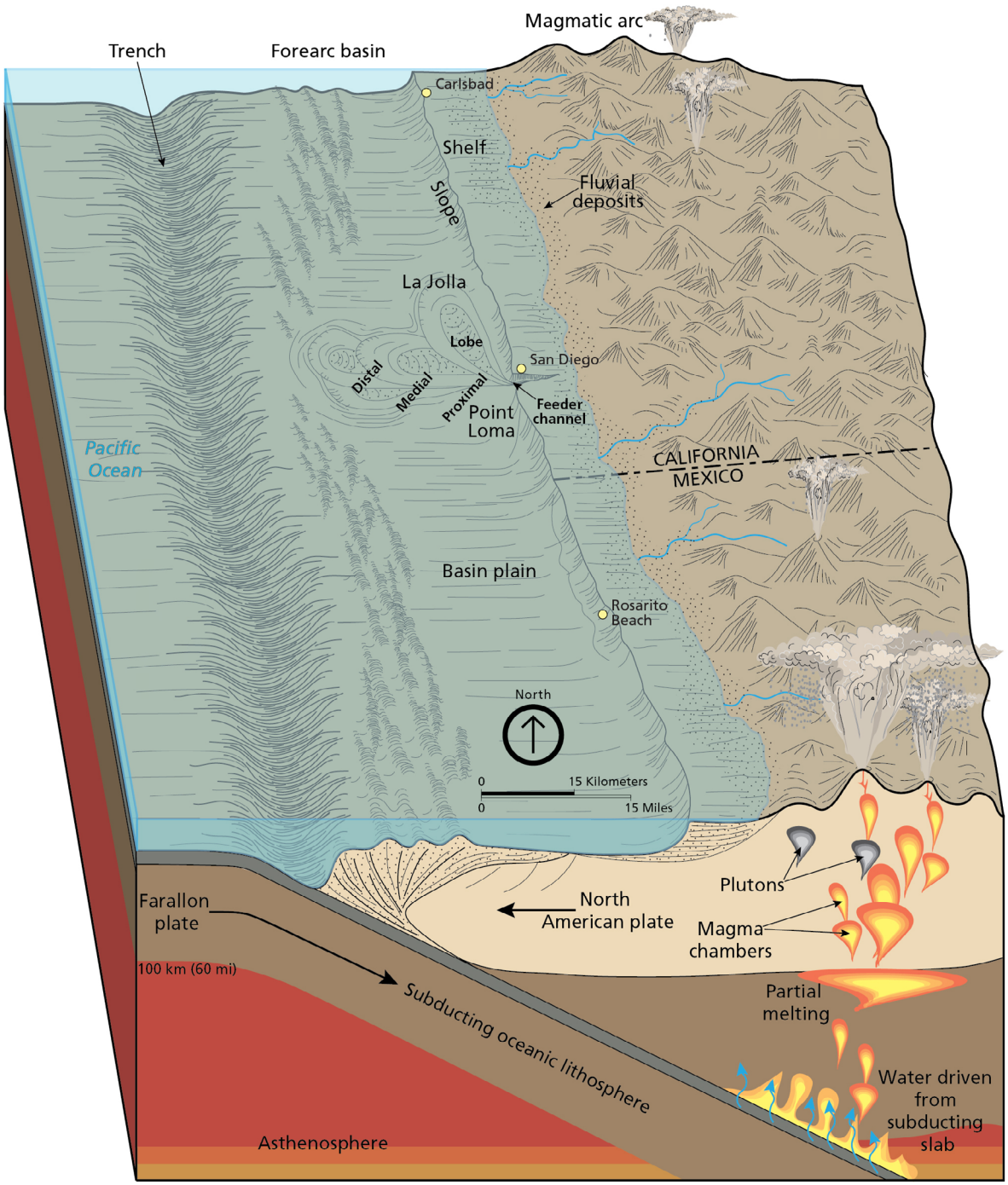


Figure 10. Graphic of the San Diego area during the Late Cretaceous Period.
Between 76 million and 72 million years ago, a huge submarine fan was building across the shelf, slope, and basin plain of the Pacific Ocean as the Farallon plate subducted beneath the North American plate off the west coast of North America. The surface expression of subduction was a deep trench. The fan, represented by the Point Loma and Cabrillo Formations in the monument, developed in a forearc basin landward of the trench. Four north–northwest-oriented fan lobes associated with the Point Loma Formation are shown in the figure. A magmatic arc (Peninsular Ranges) formed on the overriding continental plate; granitic batholiths (large bodies of igneous rock) developed in magma chambers below Earth's surface and lava flows and other volcanic materials were deposited on the surface as part of the arc. Sediment shed from the magmatic arc was deposited into the forearc basin, building up the fan. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Nilsen and Abbott (1981, figure 20) and information in Fleming (2010).

of sand and mud), though some silt and clay were deposited off axis by turbidity currents and associated "fallout" transported via suspension into the fringe parts of the submarine-fan lobe (fig. 9). In addition, six mass transport deposits (e.g., slumps and debris flows) consisting of silt to coarse sand are part of the complex in the monument; these deposits reflect a time of instability high on the marine shelf (Fleming 2010). More proximal parts of the larger fan system are exposed in the sea cliffs north of the monument.

Unlike the study conducted by Fleming (2010) for the Point Loma Formation, the Cabrillo Formation has not been analyzed using a channel–lobe complex model. However, if such as analysis was made, the cobble conglomerate (**Kccg**) would represent a main feeder channel with the medium-grained sandstone (**Kcs**) representing the proximal part of a lobe (fig. 9). (This interpretation, based on an understanding of the Fleming [2010] thesis, was verified during the GRI review process by Zane Jobe, Colorado School of Mines, research professor, email communication, 23 June 2017).

With respect to the regional plate-tectonics setting, the Peninsular Ranges—which represent a "magmatic arc" (arcuate line of plutons, volcanic rocks, or active volcanoes) associated with a subduction zone—were the source of the sediment for the submarine fan (fig. 10). During the Cretaceous Period, the oceanic Farallon plate was subducting beneath the continental North American plate, resulting in the intrusion of a tremendous volume of magma, which crystallized to form the rocks that dominate much of the eastern Peninsular Ranges. Intrusion of voluminous magma caused the area to become uplifted. Elevation increased by 3 km (2 mi) shortly after peak magmatism. Also, the thickness of the crust increased by 20 km (12 mi) as a result of magmatism (Jiang and Lee 2016).

Erosion of the Peninsular Ranges lagged behind peak magmatism by about four million years (Jiang and Lee 2016). Erosion produced large volumes of sediment, which were transported by rivers to the west of the magmatic arc into a submerged area known as a "forearc basin" (fig. 10). The Upper Cretaceous submarine fan was deposited along the eastern edge of the forearc basin. During deposition of the Point Loma Formation, sediment was transported to the west and northwest on the marine shelf and across the basin plain. During deposition of the Cabrillo Formation, sediment was transported to the southwest (Fleming 2010).

By the Late Cretaceous Period, erosion had significantly reduced the elevated highland, stripping off much of the overlying rock cover and exposing the once deeply buried plutonic rocks (Nilsen and Abbott 1984). Erosion continued long after the cessation of magmatism, resulting in the gradual smoothing of topography and near-complete removal of excess crustal thickness by late Eocene time (Jiang and Lee 2016).

Cretaceous Rocks and Fossils

Kennedy and Moore (1971) assigned the Cretaceous strata in the San Diego area to the Rosario Group. The offshore bedrock on the western side of the monument consists of the undivided rocks of the Rosario Group (**Kuo**); in the offshore region to the east of Point Loma, undivided marine deposits (**Qmo**) of Quaternary age occur (see "Offshore Geology").

The Rosario Group is subdivided into three formations: (1) Lusardi, (2) Point Loma, and (3) Cabrillo. Onshore bedrock in the monument consists of the Point Loma (**Kp**) and Cabrillo (**Kcs** and **Kccg**) Formations (fig. 11; table 2). Rocks assigned specifically to the Lusardi Formation, the basal unit of the Rosario Group, do not occur in the monument. The Lusardi Formation is an alluvial fan deposit that developed on the western side of the Peninsular Ranges (Kennedy 1975). It consists of a pebble-to-cobble conglomerate with few sandstone lobes (Nilsen and Abbott 1981). The type section of the Lusardi Formation is exposed 3 km (2 mi) southeast of Rancho Santa Fe, California, and is more than 120 m (390 ft) thick (Kennedy and Moore 1971). The upper contact of the Lusardi Formation, which is exposed in Carlsbad 45 km (28 mi) north of San Diego, is unconformable (break in deposition; see "Unconformities") with the overlying Point Loma Formation (Nilsen and Abbott 1981).

Figure 11. Photograph of the Point Loma Formation. Alternating beds of sandstone and mudstone of the Point Loma Formation stand out in relief at this outcrop in the tidepools area of the monument. NPS photograph (Cabrillo National Monument).

Table 2. General stratigraphic column for Cabrillo National Monument.

Notes: Units include those mapped on land and in the offshore areas surrounding Point Loma. Colors are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps. Colors in map unit column correspond to the GRI poster (in pocket). The thick black line between Cretaceous units (Kcs) and Quaternary units (Qvop) denotes an unconformity (a long hiatus). The dotted black line between Point Loma Formation (Kp) and Cabrillo Formation conglomerate (Kccg) denotes a possible unconformity. Kennedy (1975) and Kennedy and Tan (2008) interpreted the Point Loma and Cabrillo Formations as conformable; Fleming (2010) suggested that they are unconformable.

Era	Period	Epoch (years ago)	Map Unit (map symbol)	Geologic Description
CENOZOIC	Quaternary	Holocene (11,700–0)	Undivided marine deposits in offshore region (**Qmo**)	Unconsolidated, commonly ponded, marine sediments (sand and silt).
		Holocene and Pleistocene (2.6 million–0)	Landslide deposits, undivided (**Qls**)	Highly fragmented to largely coherent landslide deposits composed of Upper Cretaceous sedimentary rocks and/or Pleistocene deposits.
		Pleistocene (2.6 million–11,700)	Old paralic deposits, Unit 7 (**Qop7**)	Shoreline, beach, estuarine, and colluvial (gravity-driven) deposits composed of siltstone, sandstone, and conglomerate. Associated with the Bird Rock terrace.
			Old paralic deposits, Unit 6 (**Qop6**)	Shoreline, beach, estuarine, and colluvial deposits composed of siltstone, sandstone, and conglomerate. Associated with the Nestor terrace.
			Very old paralic deposits, undivided (**Qvop**)	Shoreline, beach, estuarine, and colluvial deposits composed of siltstone, sandstone, and conglomerate. Associated with now emergent, abrasion platforms, such as the Linda Vista terrace.
MESOZOIC	Cretaceous	Late Cretaceous (100 million–66 million)	Cabrillo Formation (**Kcs**)	Sandstone.
			Cabrillo Formation (**Kccg**)	Cobble conglomerate.
			Point Loma Formation (**Kp**)	Sandstone and siltstone.
			Undivided rocks of the Rosario Group in the offshore area (**Kuo**)	Sandstone, siltstone, and conglomerate.

Point Loma Formation

The Point Loma Formation consists of interbedded, fine-grained, dusky-yellow sandstone and olive-gray siltstone in ledgy graded beds about 20 cm (8 in) thick (Kennedy and Moore 1971) (fig. 11; table 1). Exposures of the formation wrap around Point La Jolla (north of the monument) to the tip of Point Loma (see cabr_geology.mxd). Its type section is the sea cliffs along the western side of the Point Loma peninsula (Kennedy and Moore 1971), thereby, occurring within the boundaries of the monument.

Indicative of its origin as a submarine fan (see "Paleogeographic Setting"), most of the fossils in the Point Loma Formation are marine, primarily microfossils (e.g., coccoliths and foraminifera) and mollusks. Microfossils are used to determine the ages of rocks and the water depths of depositional settings. The Point Loma Formation has yielded marine invertebrates such as bryozoans, bivalves, ammonites (an extinct group of marine mollusk with a spiral-form shell; fig. 12), and gastropods, as well as vertebrates such as sharks and boney fish. Additionally, the Point Loma Formation has notable trace fossils. Abundant invertebrate trace fossils, particularly of the trace genera *Ophiomorpha* and *Thalassinoides*, occur in the rocks at the tidepool area at the monument (fig. 13). Thus as visitors explore

Figure 12. Photograph of fossil ammonite.
Both the Point Loma and Cabrillo Formations have yielded ammonite fossils, which are indicative of a submarine setting. This specimen (*Pachydiscus catarinae*), which is now at the Natural History Museum of Los Angeles County, is from the Point Loma Formation. It was found at the tip of Point Loma (outside the monument). The scale is in centimeters. NPS photograph by Vincent L. Santucci (Geologic Resources Division).

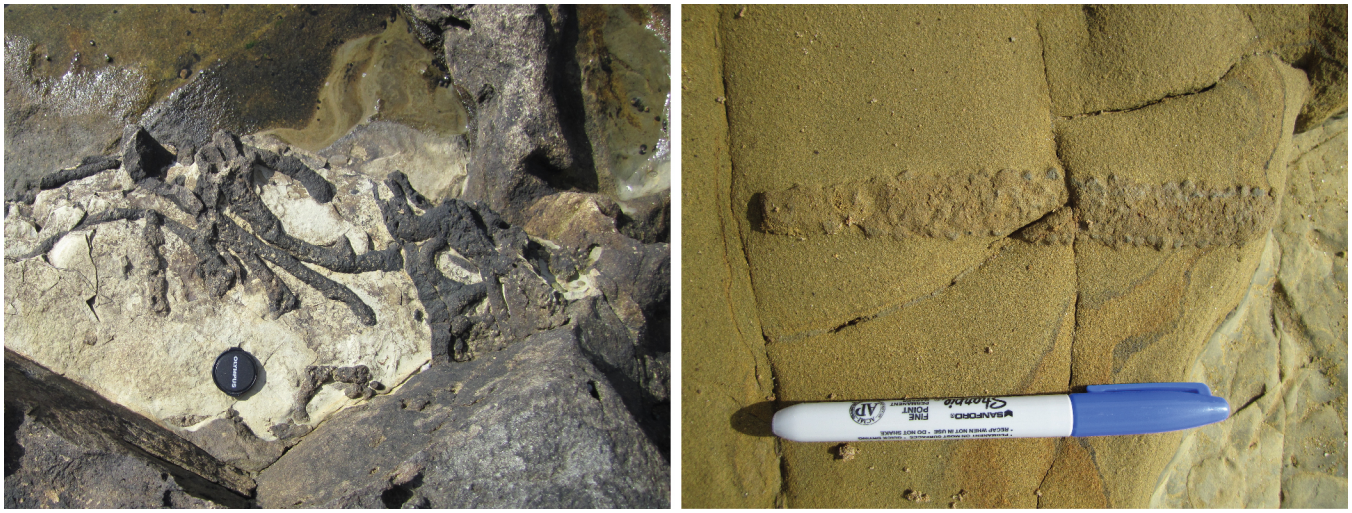


Figure 13. Photographs of trace fossils.
The Point Loma Formation at the monument contains trace fossils that preserve the life activity of burrowing marine invertebrates. The left photograph shows the ichnogenus *Thalassinoides* (three-dimensional, branched cylindrical burrows). The right photograph shows the ichnogenus *Ophiomorpha* (vertical and horizontal cylindrical burrows). Lens cap and marker for scale. NPS photographs (Cabrillo National Monument).

Figure 14. Photograph of fossil cycad.
A cycad leaf (specimen SDNHM 48361) from the Point Loma Formation at the monument is on display at the San Diego Natural History Museum. The scale is in centimeters. NPS photograph by Vincent L. Santucci (Geologic Resources Division).

Figure 15. Photograph of the Cabrillo Formation.
The Cabrillo Formation overlies the Point Loma Formation. It formed in the "feeder channel" of a submarine fan and consists of cobble conglomerate and sandstone. The type section lies east of the new Point Loma lighthouse (Point Loma Light Station), where about 81 m (266 ft) of the formation is exposed (fig. 4). The outcrop shown here occurs along the Cabrillo Memorial Road on the western slope of the Point Loma peninsula. NPS photograph by Austin Parker (Cabrillo National Monument).

clefts in the rocks for modern-day organisms, they also have the opportunity to observe the activity (trace fossils) of ancient life-forms.

The most unusual fossil found in the Point Loma Formation at the monument to date was a large cycad leaf (fig. 14). It was discovered at the tidepool area and is now on display at the San Diego Natural History Museum (Koch and Santucci 2003; Tweet et al. 2012). This specimen has not been formally described in the literature. Other interesting finds in the Point Loma Formation, though not from within the monument, are large ammonites with epibiont (an organism that is attached to and lives on the surface of another organism) thorny oysters, and a partial tooth of a mosasaur (giant marine lizard) (see scoping summary by KellerLynn 2008a). Of possible interest for interpretation, the Point Loma Formation yielded *Aletopelta coombsi*—the first dinosaur named from California. It is either an ankylosaurid (Ford and Kirkland 2001) or a nodosaurid (Coombs and Deméré 1996; Hawakaya et al. 2005). The Point Loma Formation in the monument has yet to yield a dinosaur fossil, but scoping participants mentioned a dinosaur fossil having been found in the Point Loma Formation at nearby Palomar Airport; that specimen is probably *Aletopelta* (Justin Tweet, NPS Geologic Resources Division, associate, written communication, 10 January 2017).

Cabrillo Formation

The Cabrillo Formation consists of mostly massive (lacking sedimentary structures) medium-grained sandstone (**Kcs**) and cross-bedded (composed of strata inclined at an angle) cobble conglomerate (**Kccg**) (fig. 15). The type section for the Cabrillo Formation is in the sea cliffs 250 m (820 ft) east of the new Point Loma lighthouse (Point Loma Light Station), where the base of the formation is 30 m (100 ft) above mean sea level and the top of the formation is at the top of the cliff (Kennedy and Moore 1971). About 81 m (266 ft) of the formation is exposed in the type section (fig. 4). Elsewhere, even greater thicknesses are exposed; for example, in the False Point sea cliff at Bird Rock, north of the monument, the exposure is 170 m (560 ft) thick (Kennedy and Tan 2008).

The Cabrillo Formation does not contain as rich a fossil record as the Point Loma Formation, but has yielded wood fragments, coral, brachiopods, bivalves, ammonites, gastropods, and echinoderms from a series of localities along the sea cliffs on the east side of the Point Loma peninsula, including exposures in the monument (Dawson 1978). Many fossils discovered in the Cabrillo Formation are reworked from the underlying Point Loma Formation or from older deposits of the Cabrillo Formation itself (Dawson 1978; Thomas A. Deméré, personal communication, November 2011, in Tweet et al. 2012, p. 20). An interesting find was a shark tooth from the genus *Squalicorax*, which was in a clast recovered from a channel cut into sandstone (Koch and Santucci 2003) either just within or just outside the northern boundary of the monument; it was probably reworked (Thomas A. Deméré, personal communication, November 2011, in Tweet et al. 2012, p. 20). Foraminifera (Anderson 1962), coccoliths (Bukry and Kennedy 1969), and bryozoans (Taylor 2008) have also been reported from the Cabrillo Formation on the Point Loma peninsula.

According to Kennedy and Tan (2008), the Cabrillo conglomerate (**Kccg**) consists of pieces of plutonic and metavolcanic rocks (Kennedy and Tan 2008). Other investigators describe the conglomerate as also containing metasedimentary and metamorphic rocks (Nilsen and Abbott 1984). Regardless, these rock fragments—including pieces of the late Mesozoic batholitic complex, Santiago Peak Volcanics and Julian Schist—point to a chiefly local provenance in the Peninsular Ranges to the east (Nilsen and Abbott 1984). Volcanoes of the Peninsular Ranges were erupting during the Late Jurassic Period, approximately 150 million years ago (Bushee et al. 1963). Mudstone clasts in the conglomerate are intraformational in origin, although some may be derived from erosion of the underlying Point Loma Formation (Nilsen and Abbott 1984).

The Cabrillo sandstone (**Kcs**) in the monument also bears connections to the Peninsular Ranges. A large greenish boulder of Santiago Peak Volcanics is embedded in the sandstone in the road cut to the left of the monument's entrance station. Abbott (1999) interpreted this boulder, and others at the same level, as representing faulting that offset the submarine fan. Faulting created a steep scarp or underwater cliff where Santiago Peak Volcanics were exposed and then fell in large chunks from the fault scarp directly onto the submarine fan. As fan deposition continued, more sediment accumulated and the boulders became incorporated into the sandstone.

Distinctive dark-colored boulders of the Santiago Peak Volcanics also occur in the tidepool area of the monument (fig. 16). Like the boulder at the entrance station, these rocks were once embedded in the Cabrillo sandstone. As the sandstone eroded away, the resistant boulders remained but became scattered along the coastline via mass-wasting (gravity-driven) processes (National Park Service 2016a).

Figure 16. Photograph of Santiago Peak Volcanics boulders.
The distinctive boulders at the tidepools in the monument have had a long history. They originated as lava erupted in the Peninsular Ranges during the Late Jurassic Period (approximately 150 million years ago). The material (Santiago Peak Volcanics) was uplifted and exposed in a fault scarp in the Upper Cretaceous submarine fan and fell to the surface of the fan, where they became encased in sand. Much later, as waves have whittled away the sea cliffs, the resistant boulders have remained while the surrounding Cabrillo sandstone has eroded away. NPS photograph (Cabrillo National Monument).

Offshore Geology

The GRI GIS data for Cabrillo National Monument are distinctive because they include rocks and unconsolidated deposits in offshore areas, that is, below the surface of the Pacific Ocean and San Diego Bay. The offshore geology within the monument consists of two units: (1) undivided rocks of the Rosario Group in the offshore area (**Kuo**) and (2) undivided marine deposits in offshore region (**Qmo**).

Undivided rocks of the Rosario Group in the offshore area (**Kuo**) is composed of sedimentary rocks (conglomerate and sandstone; table 1) of the Lusardi Formation, which is not exposed in the monument, as well as the Point Loma Formation (**Kp**) and Cabrillo Formation (**Kcs** and **Kccg**), which comprise the onshore bedrock. Undivided rocks of the Rosario Group in the offshore area (**Kuo**) were mapped on the western side of the monument, in the tidepool area (Kennedy and Tan 2008).

Just beyond the eastern boundary of the monument, undivided marine deposits in offshore region (**Qmo**) were mapped underlying the Pacific Ocean and San Diego Bay. Kennedy and Tan (2008) described this unit as unconsolidated, often ponded marine sediments, composed mostly of very fine- to medium-grained sand and silt. The map unit description does not provide details of the unit's origin, but "ponded" may be interpreted as resulting from a sediment slurry flowing into a low spot on the seafloor. Hersey (1965) described deep-sea sediment ponds in other parts of the world; the ones in a basin of the Tyrrhenian Sea (west of Italy) are similar to basins off the coast of California, potentially including the seafloor covered by **Qmo** in the vicinity of the monument.

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 rock record in the monument documents a 70-million-year unconformity between the Late Cretaceous Period and Quaternary Period (fig. 17; table 2; see "Geologic History").

The source maps for the GRI GIS data (Kennedy 1975; Kennedy and Tan 2008) and other studies (e.g., Nilsen and Abbott 1981) have interpreted the Point Loma and Cabrillo Formations as conformable. However, the abrupt contact between the lower mudstone of the Point Loma Formation and the upper channelized sandstone and conglomerate of the Cabrillo Formation at the type sections and the paleocurrent-direction change from west–northwest in the Point Loma Formation to southwest in the Cabrillo Formation indicate that these units are unconformable (Fleming 2010).

Faults

Faults are fractures in Earth's crust along which movement has taken place (fig. 18). Movement along faults causes earthquakes (see "Earthquakes"). Faults in which the movement is primarily vertical are called "dip-slip faults" because the displacement is along the inclination, or dip, of the fault plane. Faults in which the dominant displacement is primarily horizontal are called "strike-slip fault" because displacement is along the trend, or strike, of the fault. Strike-slip faults are the predominant type in southern California, though

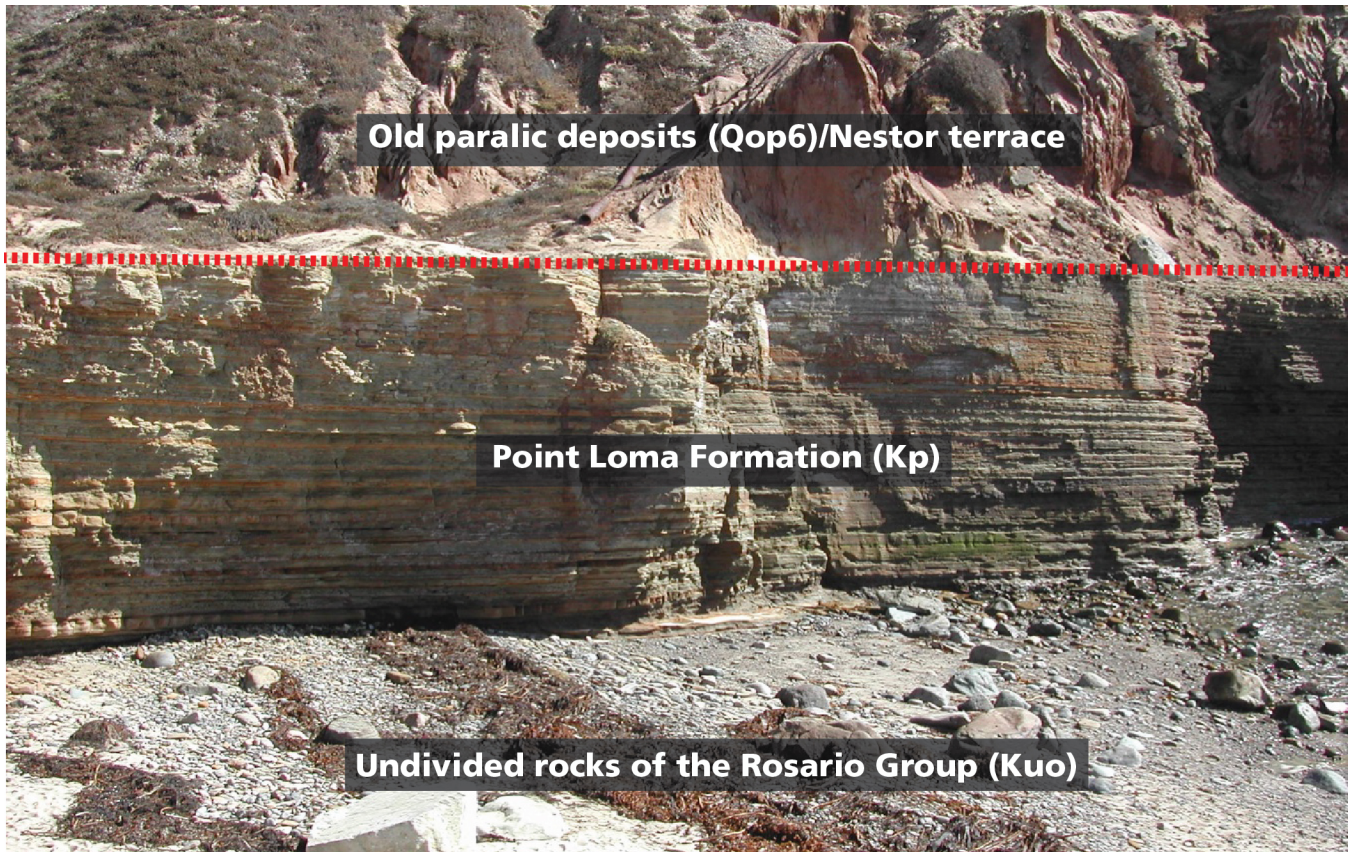


Figure 17. Photograph of strata at the tidepools.
The sea cliffs at the tidepools in the monument consist of rocks of the undivided Rosario Group (Kuo) at the base; these rocks occur in the intertidal zone and are submerged during high tides. The Point Loma sandstone (Kp) makes up the main cliff face, which is about 5–6 m (15–20 ft) high. Overlying the Point Loma Formation are old paralic deposits (Qop6), which are associated with the Nestor terrace. The hashed red line delineates the unconformity caused by erosion between the Late Cretaceous and Quaternary Periods. NPS photograph from National Park Service (2016a).

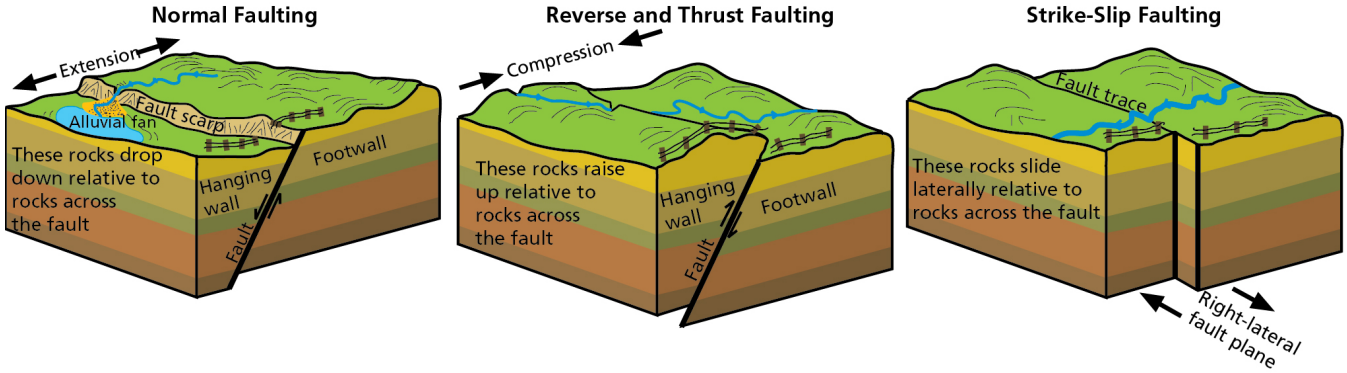


Figure 18. Graphic of fault types.
Movement occurs along a fault plane. Footwalls are below the fault plane and hanging walls are above. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging 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 (horizontal). When movement across the fault is to the right, it is a right-lateral strike-slip fault, as illustrated above. When movement is to the left, it is a left-lateral strike-slip fault. The Rose Canyon fault zone is a right-lateral strike-slip fault, though segments of compression and extension occur. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

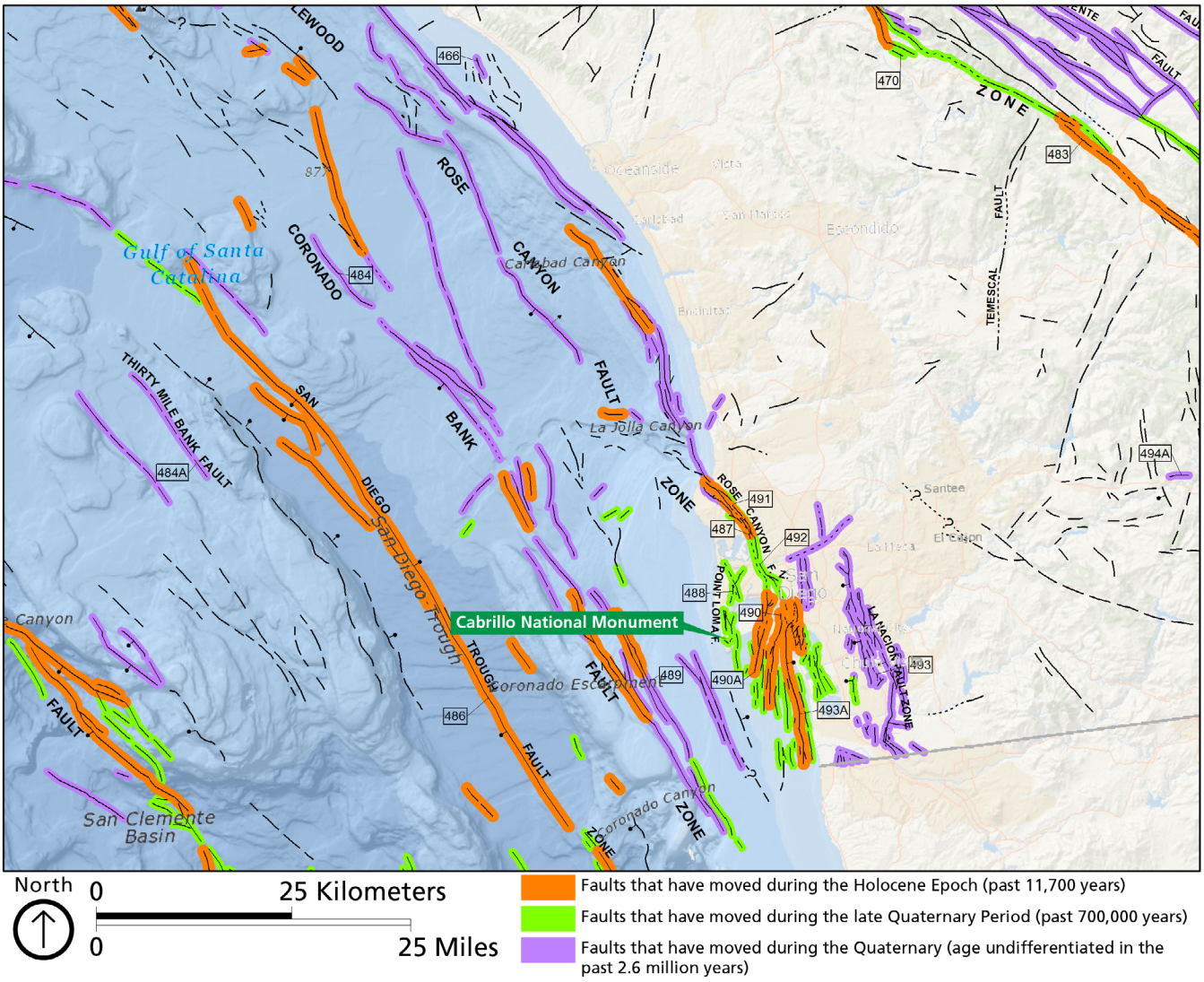


Figure 19. Screen capture of fault activity map of California.
Many active faults occur in the vicinity of the monument. The Rose Canyon fault zone is the primary fault of interest for San Diego. Orange lines indicate faults that have moved during the Holocene Epoch (past 11,700 years). Green indicates movement during the late Quaternary Period (past 700,000 years). Purple indicates a Quaternary fault (age undifferentiated in the last 2.6 million years). The numbers in boxes on the figure refer to a list of "classified faults" in Jennings and Bryant (2010): 487 = Mission Bay fault, 488 = Point Loma fault zone, 489 = Coronado Bank fault zone (offshore Coronado Bank section), 490 = Coronado fault, 490A = Spanish Bight fault, 491 = Rose Canyon fault zone, and 492 = Old Town fault (Rose Canyon fault segment). Source: California Geological Survey data at http://maps.conservation.ca.gov/cgs/fam/ (accessed 16 May 2017). Basemap is Esri "Oceans" layer with data from Esri, GEBCO, NOAA, National Geographic, Garmin, HERE, Geonames.org, and other contributors.

dip-slip movement played an important role in uplift of the sea cliffs of Point Loma.

Much of coastal San Diego lies astride the Rose Canyon fault zone, which is composed of the Rose Canyon and other associated faults, including the Spanish Bight and Silver Strand faults in the vicinity of the monument. The Rose Canyon fault zone runs both onshore and offshore (fig. 19). It is characterized by right-lateral strike-slip movement. "Right-lateral" describes the sense of motion along the fault where the opposite block across the fault line appears to move to the right. A left-lateral strike slip fault is where the opposite block appears to move to the left (fig. 18). The slip rate on the Rose Canyon fault is 1.1 mm (0.04 in) per year (Southern California Earthquake Data Center 2016).

The Rose Canyon fault zone extends to the north and joins the Newport–Inglewood fault zone. Offshore, the Palos Verdes Hills–Coronado Bank, San Diego Trough, and San Clemente fault zones are generally parallel to the Rose Canyon fault zone. All these faults are included in the GRI GIS data. In addition, six fault strands cutting across Point Loma occur in the monument. These fault strands are unnamed in the GRI GIS data, but the fault activity map of California (see http://maps.conservation.ca.gov/cgs/fam/), which was based on Jennings and Bryant (2010), refers to them as part of the Point Loma fault.

Although motion on the Rose Canyon fault zone is generally considered right-lateral strike slip (Kennedy 1975), individual strands within the fault zone display various combinations of dip slip (vertical) and strike slip (horizontal) motion (Lindvall and Rockwell 1995). These changes in relative motion have locally resulted in the uplift of Soledad Mountain (commonly referred to as "Mount Soledad"), the downwarping of Mission Bay, the rise of Point Loma, and the drop of San Diego Bay (fig. 1). Thus San Diego owes much of its aesthetic beauty to this fault zone (Abbott and Rockwell 2004). Similarly, activity on the Rose Canyon fault zone explains why the Point Loma (**Kp**) and Cabrillo (**Kcs** and **Kccg**) Formations, which were deposited as a submarine fan deep in the Pacific Ocean, are now above sea level. The formations were raised are part of a syncline (U-shaped fold) with Soledad Mountain as the syncline's northern high end, 249 m (817 ft) above sea level, and Point Loma as the syncline's southern high end, 129 m (422 ft) above sea level. Moreover, San Diego would not have a harbor and probably would not have been settled as it was or had the cultural history that it did without the Rose Canyon fault zone. On the other hand, the Rose Canyon fault zone is responsible for earthquake hazards and risk in the San Diego area (see "Earthquakes").

Marine Terraces, Uplift, and Fossils

Erosion of the shoreline produces wave-cut platforms (referred to as "abrasion platforms" by Kennedy and Tan 2008) in bedrock. This process took place in the past at former sea-level highstands and is taking place today. Wave-cut platforms represent former shorelines where nearshore marine, beach, estuarine, lagoonal, and dune sediments accumulated. From a geologic materials perspective, these unconsolidated sediments atop abrasion platforms are referred to as "paralic deposits"; very old paralic deposits (**Qvop**) and old paralic deposits (**Qop6** and **Qop7**) were mapped by Kennedy and Tan (2008) in the monument. From a geomorphic perspective, these sediment-covered, wave-cut platforms are landforms called "marine terraces." The marine terraces along the San Diego coast sit high above sea level today (Kern and Rockwell 1992). They were abandoned primarily as a result of uplift associated with the Rose Canyon fault zone (see "Faults"). Uplift has taken place at an average rate of 13–14 cm (5–6 in) per 1,000 years in the San Diego region.

Although terraces have been raised tectonically, they remain essentially horizontal. For instance, the Linda Vista terrace is conspicuously level. In San Diego, this high topographic surface is referred to as the Linda Vista Mesa, and much of the city was built on it (see "Linda Vista Terrace").

A series of 21 marine terraces occurs in the San Diego area (Kennedy and Tan 2008). These are represented by 13 "**Qvop**" and eight "**Qop**" units in the GRI GIS data. They range in age from perhaps 1.5 million to 45,000 years old.

Three marine terraces occur in the monument (fig. 20). From oldest to youngest they are the Linda Vista, Nestor, and Bird Rock terraces, approximately 855,000, 120,000, and 80,000 years old, respectively (Kern 1977; Wehmiller et al. 1977; Kennedy et al. 1982; Kern and Rockwell 1992). Where divided into units elsewhere in the San Diego area (see GRI GIS data), very old paralic deposits, Unit 9 (**Qvop9**) rest on the Linda Vista terrace (see GRI GIS data); these deposits are undivided (**Qvop**) in the monument. Deposits that comprise the Linda Vista terrace have been mapped as the Lindavista Formation elsewhere in California (Hanna 1926; Gastil et al. 1975). Old paralic deposits, Unit 6 (**Qop6**) rest on the Nestor terrace, and old paralic deposits, Unit 7 (**Qop7**) rest on the Bird Rock terrace in the monument (Kennedy and Tan 2008). Deposits associated with the Nestor and Bird Rock terraces have been mapped as the Bay Point Formation elsewhere in California (Hertlein and Grant 1939; Moore 1972).

Linda Vista Terrace/Very Old Paralic Deposits (Qvop9)

The Linda Vista terrace is approximately 114 m (374 ft) above sea level today (Kennedy and Tan 2008). It occupies the highest topographic position in the monument. The Old Point Loma Lighthouse, Assistant Keeper's Quarters, and Whale Overlook rest on this terrace level (see poster, in pocket).

The Linda Vista terrace is an estimated 855,000 years old. No accurate paleo–sea levels are available for terraces older than approximately 500,000 years (Kennedy and Tan 2008, sheet 2), so the Linda Vista terrace's relationship to present-day sea level is unknown.

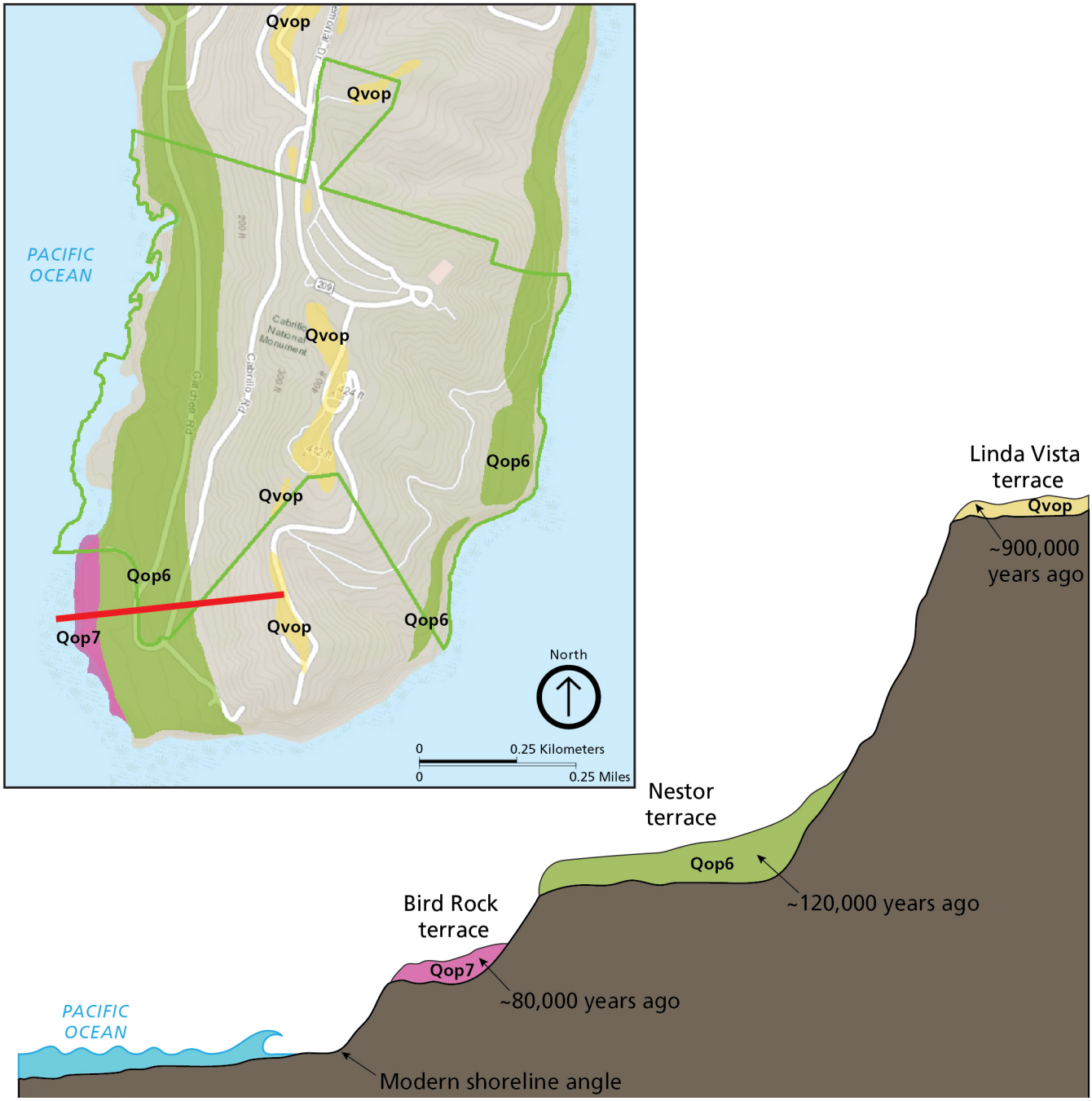


Figure 20. Graphic of marine terraces.
This figure shows a generalized cross section for the area underlying the red line drawn on the map. The colors of the marine terraces on the graphic match those of the map units on the inset map. Marine terraces are uplifted, "abandoned," shorelines, now raised above wave activity. Three levels of marine terraces occur at the monument. The highest and oldest is the Linda Vista terrace; very old paralic deposits, undivided (Qvop) are associated with this terrace. The Linda Vista terrace is about 114 m (374 ft) above sea level today. The Old Point Loma Lighthouse rests on this terrace. The middle terrace is the Nestor terrace; old paralic deposits, Unit 6 (Qop6) are associated with this terrace. The Nestor terrace is about 22 m (72 ft) above sea level today. The trail leading to the tidepool area is on this terrace (fig. 21). The youngest and lowest terrace is the Bird Rock terrace; old paralic deposits, Unit 7 (Qop7) are associated with this terrace. The Bird Rock terrace is about 10 m (33 ft) above sea level today. The ages of the terraces represent the timing of wave activity that cut the platforms as well as the accumulation of paralic deposits atop the wave-cut platforms. Fossils in the paralic sediments were used in dating. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Abbott and Rockwell (2004, p. 17).

Figure 21. Photograph of trail leading to the tidepools.
The trail leading to the tidepool area of the monument represents a previous shoreline where waves cut a platform into bedrock (Point Loma Formation). Old paralic deposits, Unit 6 (Qop6) accumulated atop the wave-cut platform around 120,000 years ago, which was moved to its present position by regional uplift. The platform and overlying deposits compose the Nestor terrace. NPS photograph from National Park Service (2016a).

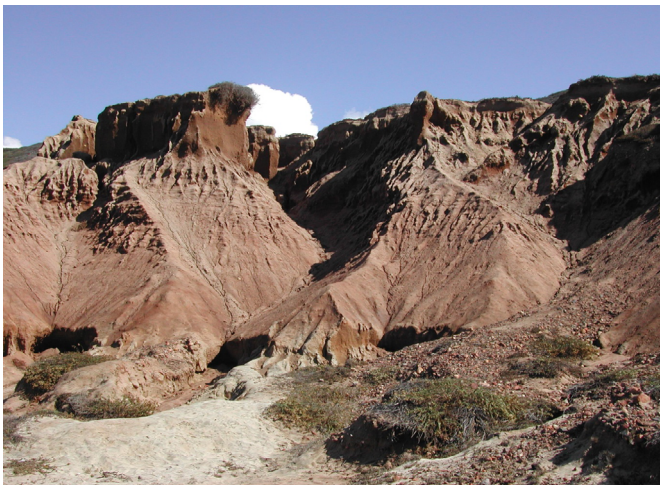


Figure 22. Photograph of old paralic deposits (Qop6).
Red sands are part of the Nestor terrace in the vicinity of the tidepools at the monument. This sand accumulated about 120,000 years ago and is much younger than the Upper Cretaceous submarine fan upon which it lies. NPS photograph from National Park Service (2016a).

The fossil assemblage associated with the Linda Vista terrace is not as diverse as that of the younger terrace units, and it is not known to be fossiliferous at the monument (Tweet et al. 2012). Elsewhere, fossils include bivalves, gastropods, barnacles, echinoids, and worm tubes (Kennedy 1973a).

Nestor Terrace/Old Paralic Deposits (Qop6)

The Nestor terrace is about 22 m (72 ft) above present-day sea level (Kennedy and Tan 2008). It developed when sea level was 6 ± 4 m (19 ± 13 ft) higher than today (Kern 1977). The slope above the tidepools is mostly composed of the 120,000-year-old Nestor terrace, and the trail leading to the tidepools crosses it (fig. 21). In addition, the cliff top on the western side of the monument consists of old paralic deposits (**Qop6**) associated with the Nestor terrace (fig. 22).

The Nestor terrace has a rich fossil assemblage (Kern 1977). Nearly 275 species of fossils have been identified from it, including corals, chitons (sea cradles), bivalves, gastropods, scaphopods, barnacles, crabs, echinoids, and worm tubes (Kern 1977; Tweet et al. 2012).

Bird Rock Terrace/Old Paralic Deposits (Qop7)

The Bird Rock terrace, which is about 10 m (33 ft) above sea level today, developed when sea level was 14 ± 2 m (46 ± 7 ft) lower than today (Kern 1977). The 80,000-year-old Bird Rock terrace is exposed in the tidepool area of the monument (see poster, in pocket).

More than 250 species of fossils have been identified from the Bird Rock terrace, including coralline algae, corals, bryozoans, brachiopods, chitons, bivalves, gastropods, scaphopods, polychaete worms, barnacles, decapod crustaceans (crabs, lobsters, and allies), echinoids, shark teeth, stingray teeth and stingers, bony fish otoliths, miscellaneous bones, and sponge borings (trace fossils) (Kennedy and Shiller 2011; Tweet et al. 2012).

Sea Cliffs, Sea Caves, and Other Coastal Features

Around Point Loma, erosion has created an irregular shoreline (fig. 23), consisting of vertical or nearly vertical sea cliffs punctuated by surge channels (linear waterways in rock where breaking waves cause inflow and outflow of water), sea caves, blowholes (nearly vertical hole in the roof of a sea cave), coves, and an occasional sea stack, arch, or pillar (fig. 24; Abbott and Rockwell 2004; Young et al. 2011). In addition, a few pocket beaches occur at the base of the sea cliffs, namely on the eastern side (bayside) of the monument. The beaches at the monument are too small to have been mapped at a scale of 1:100,000, but outside the

Figure 23. Photograph of sea cliffs on the west side of the monument.
Sea cliff erosion has resulted in the irregular shape of the shoreline at the monument. Note the Peninsular Range and San Diego Bay in the background. The Cabrillo Formation (Kcs and Kccg) is exposed in the road cut along the higher road. California Coastal Records Project, Image 200604774, taken 19 October 2006. Copyright © 2002–2018 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.californiacoastline.org.

monument, marine beach deposits (**Qmb**) were mapped (see GRI GIS data).

Sea cliffs in the monument are composed of the Point Loma and Cabrillo Formations. On the bayside of the monument, the Cabrillo Formation makes up the cliffs, with the sandstone (**Kcs**) and conglomerate (**Kccg**) dominating toward the north and south, respectively. On the western side (ocean side) of the monument, the sea cliffs are composed of the Point Loma Formation (**Kp**). Paralic deposits, mostly **Qop6**, form the upper part of the cliffs at the monument.

The stratigraphic arrangement of bedrock underlying surficial deposits creates a resistant-at-bottom cliff profile. The lower, part of the cliff profile forms vertical to near-vertical cliffs, more than 90 m (295 ft) high in some areas, whereas the upper part of the cliff profile forms gently inclined slopes (Spaulding and Crampton 2001).

The upper portion of the cliffs is subject to both marine and subaerial erosion. Processes include wave spray and wave splash during high seas or storm events; salt crystallization in rock fractures; caving of oversteepened slopes caused by the erosion of underlying cliff-forming bedrock; animal burrowing and human excavation; human-induced erosion, including climbing on bluffs and channelized footpaths; and wind, rain, irrigation, and uncontrolled surface runoff (Spaulding and Crampton 2001) (see "Slope Hazards").

Erosion of the lower cliff profile is primarily the result of marine processes. The amount of wave energy impacting a sea cliff is locally controlled by seafloor bathymetry, which is influenced by offshore geology, including lithology (rock and mineral characteristics)

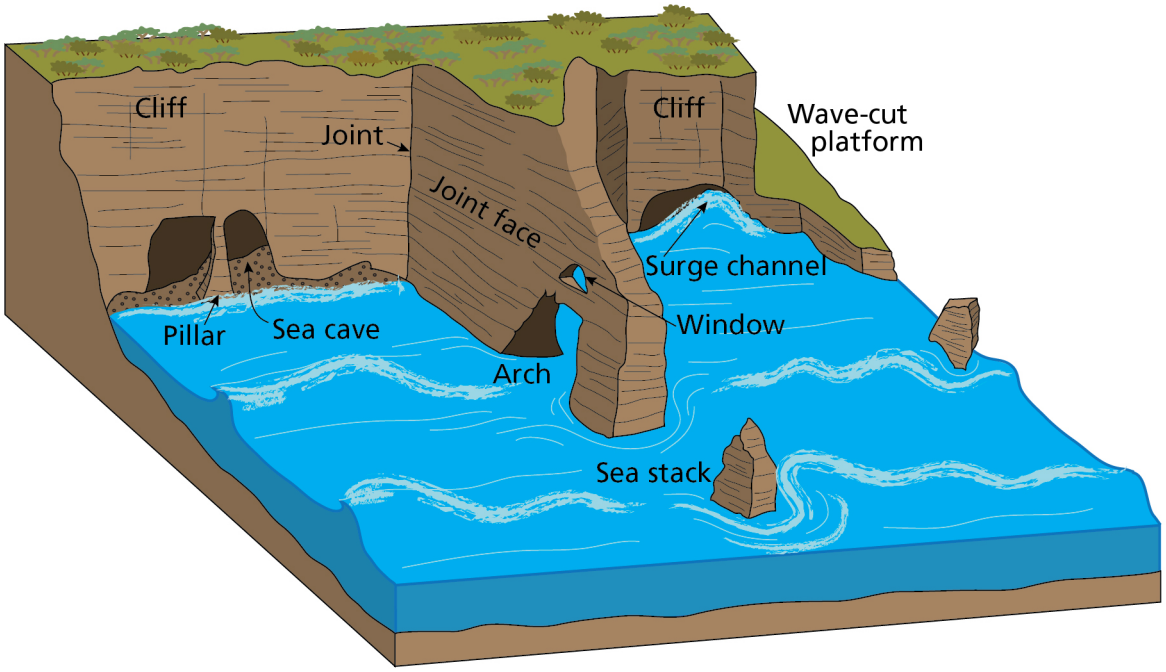


Figure 24. Graphic and photographs of coastal features on Point Loma.
Ocean waves carve the exposed bedrock at the monument into cliffs, surge channels, sea caves, wave-cut platforms, arches, pillars, and sea stacks. The graphic also shows a window; the accompanying photograph is the "beginnings" of a window (i.e., not eroded completely through the sea stack). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Nuhfer and Dalles (2004, figure 9). NPS photographs (Cabrillo National Monument). NPS photograph of wave-cut platform by Vincent L. Santucci (Geologic Resources Division).

and faulting (Crampton 2001). During storms, high-energy waves erode the faces of the cliffs. According to scoping participants, southeast-facing slopes at the monument are particularly susceptible to wave activity (see KellerLynn 2008a). Direct wave impacts acting on joints tend to wedge and cleave sections of rock out of the cliff face (fig. 25). Two prominent vertical joint sets cut the Point Loma peninsula at intersecting angles that strike N30° to 40°E and N40° to 50°W. Large rectangular blocks have been formed by the intersection of these joint sets. Erosion by wave action takes place readily along these joints (Kennedy 1973b).

As waves constantly bombard and push into these joints, they widen and deepen, forming caves. Cave formation is aided by the concentration and agitation of

Figure 25. Photographs of cliff failure.
On 21 May 2011, a large chunk of Point Loma sandstone broke away from the cliff after a night of large waves at a 2-m (6-ft) high tide. The event highlights the potential for sudden changes to occur (overnight) along the sea cliffs in the monument. The right photograph shows a view from above, looking down about 5 m (15 ft) from what remains of the edge. NPS photographs from National Park Service (2016a).

abrasive sand particles in the moving water. Continued growth can form caves more than 30 m (100 ft) long and 10 m (30 ft) wide (Abbott and Rockwell 2004). Cave erosion progresses until a cave roof collapses. If only part of a roof initially collapses, a blowhole or natural bridge forms. Upon later removal of a natural bridge, or where complete roof failure takes place all at once, coves develop (Kennedy 1973b). Between coves, headlands may form and project seaward into the ocean or bay.

Sea caves are of particular interest because their identification and protection is required by law (see Appendix B). The best developed caves on Point Loma are found along a 2-km (1-mi) stretch of Sunset Cliffs (Pipkin 1955), north of the monument. Sea caves also occur within the monument and are associated with hazardous conditions and other resource management issues (see "Cave Resource Management").

Figure 26. Photographs of tidepool area at low tide and high tide.
Tidepooling is best at negative low tides (upper photograph) when the depressions and clefts eroded into bedrock are exposed and sea life is revealed. As shown in the photographs, low tide was -0.5 m (-1.5 ft); high tide was +2.3 m (+7.5 ft). NPS photographs available at https://www.nps.gov/cabr/learn/photosmultimedia/photogallery.htm (24 July 2017).

Tidepools

The National Park Service administers approximately 1.5 km (1 mi) of shoreline on the western side of the monument. The area—referred to as the "rocky intertidal zone" (occurring between high tide and low tide) as well as the "tidepool area" (pools of water left by an ebbing tide in rock basins)—is composed of the Point Loma Formation (**Kp**) onshore and the undivided rocks of the Rosario Group (**Kuo**) offshore (see poster, in pocket). Tidepools form where uneven erosion has left depressions and clefts in the bedrock. In addition to wave erosion, some organisms actively erode and sculpt the rock surfaces (Abbott and Rockwell 2004).

The monument's tidepools host among the largest and most diverse habitats in San Diego County (Becker 2006). Many types of mollusks that require attachment to hard surfaces live in the monument's tidepools (Abbott and Rockwell 2004). Marine plants and animals living in the rocky intertidal zone have adapted to harsh conditions of pounding surf, cyclic exposure to sun and drying wind, and sharp changes in temperature and salinity (National Park Service 2007). These conditions have resulted in a distinctive community of marine life markedly different from the life-forms found along open-coast sandy beaches (Abbott and Rockwell 2004).

The diversity and unusual character of life in the monument's tidepools are popular draws for visitor exploration. The best time for "tide pooling" is during winter months when good negative low tides (-0.5 m [-1.5 ft] or lower) occur during daylight hours (fig. 26). During summer, the negative low tides generally take place in the middle of the night. Moreover, daily low tides in the summer are generally still too high for clear viewing of marine life because too much water remains in the tidepools for adequate access (National Park Service 2015e). Although the tidepools at the monument are arguably the best protected, publicly accessible tidepools on the southern California mainland (Becker 2006), their popularity and heavy use is a management concern (see "Monitoring the Physical Environment of Tidepools").

Aeolian Features and Processes

Aeolian (also spelled "eolian") processes refer to windblown erosion, transportation, and deposition of sediments (Lancaster 2009). Features created by aeolian processes include sand dunes, sand sheets, and loess (windblown dust). According to Abbott and Rockwell (2004), sand accumulations on Point Loma primarily form against old sea cliffs and at the fore edge of marine terraces as long, linear beach ridges.

At a scale of 1:100,000, Kennedy and Tan (2008) did not map any aeolian deposits in the monument, but scoping participants identified some small-scale aeolian features, including windblown sand and dunes in the intertidal zone (tidepools) and on the bayside of the monument. In addition, coastal dunes occur on nearby Navy lands. These probably equate to marine beach deposits (**Qmb**) in the GRI GIS data, which occur on the eastern side of the peninsula, north of the monument.

The source of windblown sand on Point Loma was probably an active beach on what would become a marine terrace. As an alternative, sand may have become available when sea level dropped and exposed a broad, sandy wave-cut platform, allowing wind to pick up and blow the sand inland from the previously submerged marine shelf. In many areas of southern California, sand is also derived from the mouths of major rivers, so the San Diego River may have provided another source of sand in the northern part of the peninsula (Abbott and Rockwell 2004).

Aeolian processes have long played a role in the landscape development of the Point Loma peninsula (KellerLynn 2008a). Habitats have evolved along with aeolian features, and aeolian processes continue to influence soil formation and the presence of particular species (e.g., *Chorizante orcuttiana*, an endangered annual flowering plant).

Iron Pisoliths

Iron pisoliths, also referred to as "nodules" or "concretions," form in the aeolian sand deposits at the monument (fig. 27). Pisoliths may compose a distinctive layer or shallow subsurface horizon that is commonly loaded with small (6–12 mm [0.25 to 0.5 in] in diameter) sandstone spheres cemented with iron.

Iron pisoliths are generally thought to form via chemical processes: As soil developed in the aeolian sands, clay minerals migrated downward along with elements such as iron and silicon. The clays, iron, and silica accumulated or precipitated in subsurface horizons or layers (Abbott and Rockwell 2004). As an alternative mode of formation, analysis of nodules in soils from a marine terrace in Santa Cruz, California, showed that the iron in the nodules was actively precipitated by fungi—a process previously associated with desert varnish. The analyzed nodules revealed morphological features suggesting microbial (fungal) precipitation of iron minerals (Schultz 2008).

Pisoliths are thought to have formed primarily under conifers during the Pleistocene Epoch (2.6 million–11,700 years ago), when cooler and wetter climate conditions than today prevailed (Johnson 1972; Abbott and Rockwell 2004). Thus, all the Point Loma localities that host pisoliths are relics of the "ice age"

Figure 27. Photograph of iron pisoliths. Iron-coated nodules or concretions, known as iron pisoliths, form in the aeolian sand deposits at the monument. The pisolith layers consist of small spheres—6–12 mm (0.25 to 0.5 in) across—that can cause slippery conditions on slopes. This photograph was taken near Sunset Cliffs (not in the monument). Photograph by Zane Jobe (Colorado School of Mines).

when pine trees were much more extensive along the coast, and conditions were similar to those of present-day central California.

Where iron pisoliths weather out of a soil horizon, they can produce slippery conditions on slopes, acting like ball bearings underfoot (Abbott and Rockwell 2004). The intersection of Osprey Street and Sunset Cliffs Boulevard (north of the monument) is a popular, geology field-trip stop and a notable location of this "hazard." The iron-nodule spheres cause slippery conditions as people walk from a small parking lot down the slope towards the coast. Scoping participants did not identify similar slopes in the monument, but layers of pisoliths are something for park managers to be aware in the event of future trail construction into aeolian deposits.

Old Point Loma Lighthouse

The Old Point Loma Lighthouse, which has become a landmark symbol for the City of San Diego, is the most prominent cultural feature at the monument. Identifying the building stone of significant cultural features, such as the lighthouse, is of interest for the Geologic Resources Inventory.

The historic structures preservation guide for the Old Point Loma Lighthouse (National Park Service 1990) noted that the walls, foundation, and exterior steps of the lighthouse are sandstone. Additionally, the retaining walls, curbs, steps, and comfort station on the lighthouse site, some walkways near the lighthouse, and the walls of the stone dwelling are sandstone (National Park Service 1993).

The exact source of the sandstone is unclear. According to the monument's website (http://www.nps.gov/cabr/learn/historyculture/the-lighthouses-of-point-loma.htm; accessed 24 July 2017), during construction of the lighthouse "workers carved sandstone from the hillside for walls. . . ." The closest hillside to the lighthouse is composed of the Cabrillo Formation (**Kcs**; see poster, in pocket). However, the historic structures preservation guide for the lighthouse noted that the sandstone was "historic material quarried on Point Loma, probably near Ballast Point" (National Park Service 1990, "Sandstone Masonry," p. CABR/04425-4). The rock underlying Ballast Point is the Cabrillo Formation (**Kcs**) (see GRI GIS data), but the quarry location of Ballast Point does not jibe with the description—"from the hillside"—as suggested on the monument's website. Another possible source of sandstone is, of course, the Point Loma Formation (**Kp**), which is exposed in sea cliffs. Further investigation is needed to accurately identify the source of the lighthouse's sandstone and to correlate this particular cultural resource with its geologic heritage.

Geologic Resource Management Issues

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

During the 2008 scoping meeting (see scoping summary by KellerLynn 2008a) and 2016 conference call, participants (see Appendix A) identified the following geologic resource management issues. They are ordered with respect to management priority.

- Climate Change Planning
- Sea Cliff Erosion
- Cave Resource Management
- Slope Hazards
- Earthquakes
- Monitoring the Physical Environment of Tidepools
- Paleontological Resource Inventory, Monitoring, and Protection
- Dredging

The park's foundation document (completed while this report was in final review) and state of the parks report (National Park Service 2013) are sources of monument-specific information for natural resource conditions and trends, and management. A draft of the foundation document (National Park Service 2016b) and the final state of the parks report were consulted during preparation of this report.

Monument managers are encouraged to contact the NPS Geologic Resources Division (http://go.nps.gov/geology) for assistance with resource inventories, assessments, and monitoring; impact mitigation, restoration, and adaptation; hazards risk management; laws, policy, and guidance; resource management planning; data and information management; and outreach and geologic-expertise programs such as Geoscientists-in-the-Parks and Mosaics in Science. Park staff can formally request assistance via https://irma.nps.gov/Star/.

The Geoscientists-in-the-Parks (see http://go.nps.gov/gip) and Mosaics in Science (see https://www.nps.gov/subjects/youthprograms/mosaics.htm) programs are internship opportunities that place scientists (typically undergraduate students) in parks to complete geoscience-related projects that may address resource management issues identified in this chapter. Projects at Cabrillo National Monument (as of July 2017) include a coastal hazard evaluation (Eshelman 2009).

Resource managers at Cabrillo National Monument may find *Geological Monitoring* (Young and Norby 2009) 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.

Climate Change Planning

The potential consequences of rapid climate change overshadow all other concerns for the natural resources at the monument (National Park Service 2013). Appendix B of this report lists various laws and policies that provide guidance pertaining to climate change, and "Additional References" provides links to websites containing information about climate change.

Sea level rise is a primary concern with respect to climate change. The monument is one of 118 parks that the National Park Service has identified as being vulnerable to sea level change (National Park Service 2013). Depending on the emissions scenario, sea level is projected to increase at the monument between 16.8 cm (0.55 ft) and 17.4 cm (0.57 ft) by 2050, and between 35.4 cm (1.16 ft) and 47.9 cm (1.57 ft) by 2100 (Caffrey 2015). The mean sea level trend for San Diego is 2.13 mm (0.084 in) per year with a 95% confidence interval of ± 0.19 mm (0.0075 in) per year based on monthly mean sea level data from 1906 to 2015; this is equivalent to a change of 0.2 m (0.70 ft) in 100 years (NOAA 2013).

Increasing sea level may lead to loss of land and critical habitat, increased erosion and/or accretion across the coastline, rising groundwater tables and salt water intrusion, loss of nearby freshwater ecosystems, and increased risk of high intensity storm events (Caffrey 2015). The monument has not been directly in the path of any hurricane-strength storms over the last century, but it has been close to at least one tropical storm path (tropical storm Jennifer-Katherine in 1963). Storms are expected to intensify over the next century. At least one hurricane should be expected to travel up to the monument by 2100 (Caffrey 2015).

During the 2008 scoping meeting, participants mentioned the possibility of higher sea level affecting ocean–land access points, which are economically important for the ports in San Diego Bay. Higher sea level will also impact the ecologically significant

intertidal zone (tidepools). Climate change impacts such as sea level rise, increased hurricane strength, and increased wave height will affect monument infrastructure, including buildings and parking lots. The infrastructure with the greatest risk for damage on the Point Loma peninsula, however, are non–National Park Service structures such as the new Point Loma lighthouse managed by the US Coast Guard and the wastewater treatment plant managed by the City of San Diego (figs. 4 and 28). Additionally, cultural resources will be affected by climate change impacts such as increased rusting, corrosion, and salt deposits due to more salt in the environment as the coastline encroaches; increased exposure to saltwater spray and temperature changes affecting iron components; and more rapid surface cracking, flaking, and sugaring of building stone and spalling of brick due to changing freeze–thaw cycles.

The National Park Service has several sources of detailed written guidance to help managers make day-to-day decisions. The primary source of guidance is *Management Policies 2006*. Other guidance includes director's orders, handbooks, and reference manuals. The Director's Orders and Related Documents website (https://www.nps.gov/applications/npspolicy/DOrders.cfm) shows the status of director's orders, handbooks, and reference manuals, as well as related memoranda, directives, and guidelines that remain in effect until superseded. Director's Order 39 and associated documents are applicable for ocean and coastal resource management. Appendix B of this report provides a listing of applicable laws, regulations, and NPS policies pertaining to coastal resources. "Additional References" provides a listing of pertinent websites for climate change, coastal, and marine resources.

The following publications may be useful for management and planning at the monument:

The *Geological Monitoring* chapter about marine features and processes (Bush 2009) describes 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.

Strategy for Enhanced Monitoring of Natural Resource Condition in North Atlantic Coastal Parks to Address the Effects of Rapid Climate Change (Stevens et al. 2010) identified critical monitoring needs and prioritized vital signs for parks in three inventory and monitoring networks: Northeast Coastal and Barrier Network, the Northeast Temperate Network, and National Capital Region Network.

"Climate Change Summary, Cabrillo National Monument, California" (Gonzalez 2015) summarizes climate trends for the area within the monument boundaries, historical impacts, and vulnerabilities in the region. Among other trends and impacts, the summary noted that the average annual temperature has increased, and sea surface temperatures in southern California and around the world have experienced warming of the top 75 m (246 ft). In addition, more days per year with a maximum temperature greater than 35°C (95°F) and an increase in 20-year storms (a storm with more precipitation than any other storm in 20 years) are projected. Increased atmospheric carbon dioxide (CO_2) concentrations from human activities have increased the acidity of ocean water around the world; this occurs when CO_2 dissolves in water and forms carbonic acid. These trends and impacts are significant for geologic features and processes at the monument, including an increase of sea cliff erosion as a result of storm activity and sea level rise, and the dissolution of the shells of many marine species, which could change the composition of beach materials and will ultimately impact paleontological resources and the rock record.

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) includes the geospatial location and approximate elevation of more than 10,000 assets (e.g., buildings, roads, trails, managed landscapes, or historic structures) in 40 coastal parks, including Cabrillo National Monument. The report incorporated information from the NPS Facilities Management Software System (FMSS) and other datasets, collaboration with park staff, and field visits to locate assets. Assets were characterized based on their overall exposure to long-term (1 meter) sea level rise and associated storm vulnerability, and were categorized as having either high exposure or limited exposure to sea level rise impacts. According to that report, the monument has 55 coastal assets, but all were determined to have "low exposure" to 1 meter of sea level rise as a result of being situated on "a rocky, high-elevation peninsula" (Peek et al. 2015, p. 147).

Coastal Adaptation Strategies: Case Studies (Schupp et al. 2015) presents case studies of the many ways that park managers are implementing adaptation strategies for threatened resources across the country. This publication does not include any examples from the monument, but some of the topics (e.g., cultural resource inventory and vulnerability assessments, and

developing multiagency vision for an urban coastline) are applicable.

Coastal Adaptation Strategies Handbook (Beavers et al. 2016) provides climate change adaptation guidance to managers in coastal parks that are vulnerable to sea level change. The handbook also provides guidance on developing communication and education materials about climate change impacts.

Cultural Resources Climate Change Strategy (Rockman et al. 2016) sets out a vision and broad approach for managing impacts to and learning from cultural resources under modern climate change. The strategy connects major directions for action from the 2010 NPS Climate Change Response Strategy and the 2014 NPS Director's Policy Memorandum "Climate Change and Stewardship of Cultural Resources."

In addition, the NPS Geologic Resources Division and NPS Climate Change Response Program are developing a sea level change and storm surge database that park managers can use for planning over multiple time horizons. The project will analyze rates of sea level change 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. Numbers from this project (Caffrey 2015) were used in the preceding discussion.

Sea Cliff Erosion

According to scoping participants, much of the cliff erosion at the monument is a result of the growth and collapse of sea caves (see "Sea Cliffs, Sea Caves, and Other Coastal Features" and "Cave Resource Management"). Because sea cliff erosion threatens cliff-top infrastructure, accurate information regarding trends and rates of coastal cliff retreat are needed for coastal planning.

Eshleman (2009) noted that monument staff would like to know how the cliffs on the west side of the peninsula are changing over time and how they are affecting marine resources located within the intertidal holdings. Also, cliffs on the west side of the monument may pose some public safety concerns because trails are located along the top of the cliffs.

The primary area of concern at the monument with respect to sea cliff erosion is where potential collapse of a sea cave in the monument is threatening the road to the Point Loma Wastewater Treatment Plant (fig. 28). The plant is administered and maintained by the City of San Diego (fig. 5). US Naval Base Point Loma surrounds the plant to the north and east; the Pacific Ocean is on the west; the monument is to the south. Access is denied through naval lands along Gatchell Road, so workers approach the plant from the south through the monument, on what is referred to as "South Access Road." Within the monument, this road is called "Cabrillo Memorial Drive." During the GRI conference call, participants discussed the potential for GRD staff to conduct a risk assessment of cave collapse at this location. Monument managers are encouraged to contact the NPS Geologic Resources Division for assistance. Monument staff can formally request assistance via https://irma.nps.gov/Star/.

During the GRI conference call, monument managers mentioned an interest in knowing more about rates of cliff erosion for park planning. Studies conducted along the Point Loma sea cliffs, in particular on the western side of the peninsula at Sunset Cliffs (north of the monument), have yielded rates of sea cliff erosion averaging 1.3 cm (0.5 in) per year over 75 years (Kennedy 1973b) to 160 cm (63 in) per year over 65 years (Hapke and Reid 2007). This large range is a result of differences in the quality of the data analyzed, time period evaluated, and the section of cliff studied (Young et al. 2011).

The area with the highest rate of cliff retreat measured by Hapke and Reid (2007)—1.6 m (5.2 ft) per year—was along a remote stretch of coast near Point Loma Nazarene University. This area has little or no fronting beach to protect the cliff base from wave attack. The cliff at water level is composed of relatively resistant sedimentary strata (Flick 2005) but is capped by soft, unconsolidated material that erodes via the formation of deep gullies.

Less is known about rates of erosion on the eastern side of the monument, which is more susceptible to landslides. In general, areas with the highest rates of cliff retreat in California occurred along high-relief coastal slopes and were associated with large, deep-seated coastal landslide complexes (Hapke and Reid 2007) (see "Slope Hazards").

The following are needed for an assessment of sea cliff erosion: (1) geomorphic analysis, including an inventory of subaqueous and subaerial geology (see Crampton 2001); (2) measurements of offshore bathymetry; and (3) research to determine historic climate conditions. The relationships between these factors provide coastal geomorphologists the necessary tools for evaluating future trends in coastal erosion (Crampton 2001). The GRI GIS data for the monument and newly compiled coastal resource datasets (see "Sea Level Rise and Climate Change Planning") may be useful for a future assessment of cliff retreat in the monument. Moreover, cooperation among the National Park Service and other

Figure 28. Photograph of Point Loma coastline.
The Point Loma Wastewater Treatment Plant is directly north of the monument boundary. The plant is susceptible to sea level rise and cliff erosion. In addition, cliff erosion has the potential to undermine the coastal road between the monument and the wastewater treatment plant. This figure highlights the primary area of concern for sea cave development and associated cliff erosion at the monument and identifies a collapsed cave roof. Figure 23 shows another view of this portion of the sea cliff. Basemap is ESRI "World Imagery" layer. Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

government agencies in future research of sea cliff erosion may be a possibility. Several other government land holders on the peninsula have a vested interest in hazard prediction and assessment (Eshleman 2009).

In the past, the NPS Geologic Resources Division has facilitated the evaluation of coastal hazards at the monument (see Eshleman 2009) and can provide assistance with geologic hazard management in parks. The NPS Geologic Resources Division Geohazards website (http://go.nps.gov/geohazards) provides more information.

Cave Resource Management

Cabrillo National Monument is one of 160 units in the National Park System with cave or karst resources. The Federal Cave Resources Protection Act of 1988 requires the following: (1) identification of "significant caves" in NPS areas, (2) the regulation or restriction of use as needed to protect cave resources, and (3) 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 Appendix B of this report).

All of the caves in the monument are sea caves (see "Sea Cliffs, Sea Caves, and Other Coastal Features"). The most noteworthy cave, referred to as "Cabrillo Sea Cave," is on the west side of the monument. This sea cave and nearby area have been closed since the 1980s due to extremely dangerous conditions (i.e., sudden and catastrophic sandstone erosion and rockfalls) and to comply with the Marine Mammal Protection Act. Marine mammals (i.e., seals and sea lions) use this

area and are protected by the act. Entry into this area is not permitted at any time, and approaching and/or disturbing marine mammals and their young are not allowed. Violators are subject to federal fines and sentencing (National Park Service 2017).

A park-specific cave management plan has not been completed for the monument. In general, development of a cave management plan includes a comprehensive evaluation of current and potential visitor use and activities and sets out a plan to study known and discover new caves. The NPS Geologic Resources Division can facilitate the development of a cave management plan. The NPS Cave and Karst website, https://www.nps.gov/subjects/caves/index.htm, provides information.

Managers may find the *Geological Monitoring* chapter about caves and associated landscapes (Toomey 2009) useful for cave management at the monument. That chapter describes 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.

Slope Hazards

A relative landslide susceptibility and landslide distribution map by Tan (1995) is a component of the GRI GIS data (fig. 29). It shows the distribution of areas susceptible to slope movements in the monument. Areas considered "most susceptible" are on the eastern half of the monument. Access is limited in this region, so landslides often go undocumented, but knowing how much land the monument is losing along the eastern peninsula as a result of cliff failure would be useful for park planning (Eshleman 2009). Eshleman (2009) reported recent evidence of a fairly large landslide along the cliffs on that side of the monument.

The tidepools are another "most susceptible" area in the monument (fig. 29). Cliff failures generally occur as rockfalls, block falls, and topples in the tidepool area (fig. 25). Other issues related to slope hazards include cave collapse (see "Cave Resource Management") and slope movements induced by earthquakes (see "Earthquakes").

Mapping by Tan (1995) showed the susceptibility to all types of slope hazards, that is, not only traditional, deep-seated landslides, which affect bedrock, but also a variety of other potentially damaging phenomena related to the behavior of mobilized slope materials such as surficial (shallow) failures, earthflows, debris flows, mudslides, rockfalls, soil creep, erosion, rapid sedimentation, and debris or mud flooding. The rates of movement of slope failures range from almost imperceptibly slow in soil creep, for example, as indicated by leaning trees or tilted poles, to extremely, even dangerously, rapid such as debris flows and rockfalls (fig. 30).

At present, the most noteworthy area susceptible to landsliding in the monument is along the Bayside Trail, which cuts across the east side of the monument (see poster, in pocket). In 2005, two large landslides destroyed sections of the trail (fig. 31). Needed repairs are estimated at $1 million (National Park Service 2013). At present, the monument does not have enough funding to repair the trail while also maintaining other high-priority assets. Therefore, repair must be deferred until such time as funding becomes available. The state of the park report (National Park Service 2013) identified the trail as both a historic structure, which is in "poor condition," and as park infrastructure, which warrants significant concern.

The Bayside Trail was originally constructed as a dirt road ("Meyler Road") by the US military. The road was used to access searchlights during World Wars I and II. The original road was merely graded without surfacing on fairly steep slopes. Today, the US Navy administers the road, now called "Sylvester Road," beyond the northern and southern boundaries of the monument. The portion of the road within the monument is now referred to as the "Bayside Trail." It connects visitors to coastal sage brush communities and a superb eastern view of San Diego Harbor, as well as coastal defense structures, which monument staff plans to interpret for visitors in the future (GRI conference call, 26 January 2016). Vehicle traffic is prohibited on the trail section within the monument.

The Bayside Trail is characterized by unstable slopes underlain by weak materials and/or affected by folding and faulting of strata (Tan 1995). Factors that contribute to landsliding along the trail include (1) past construction and (2) water seeps that enhance mobility. Military construction over the first 50 years

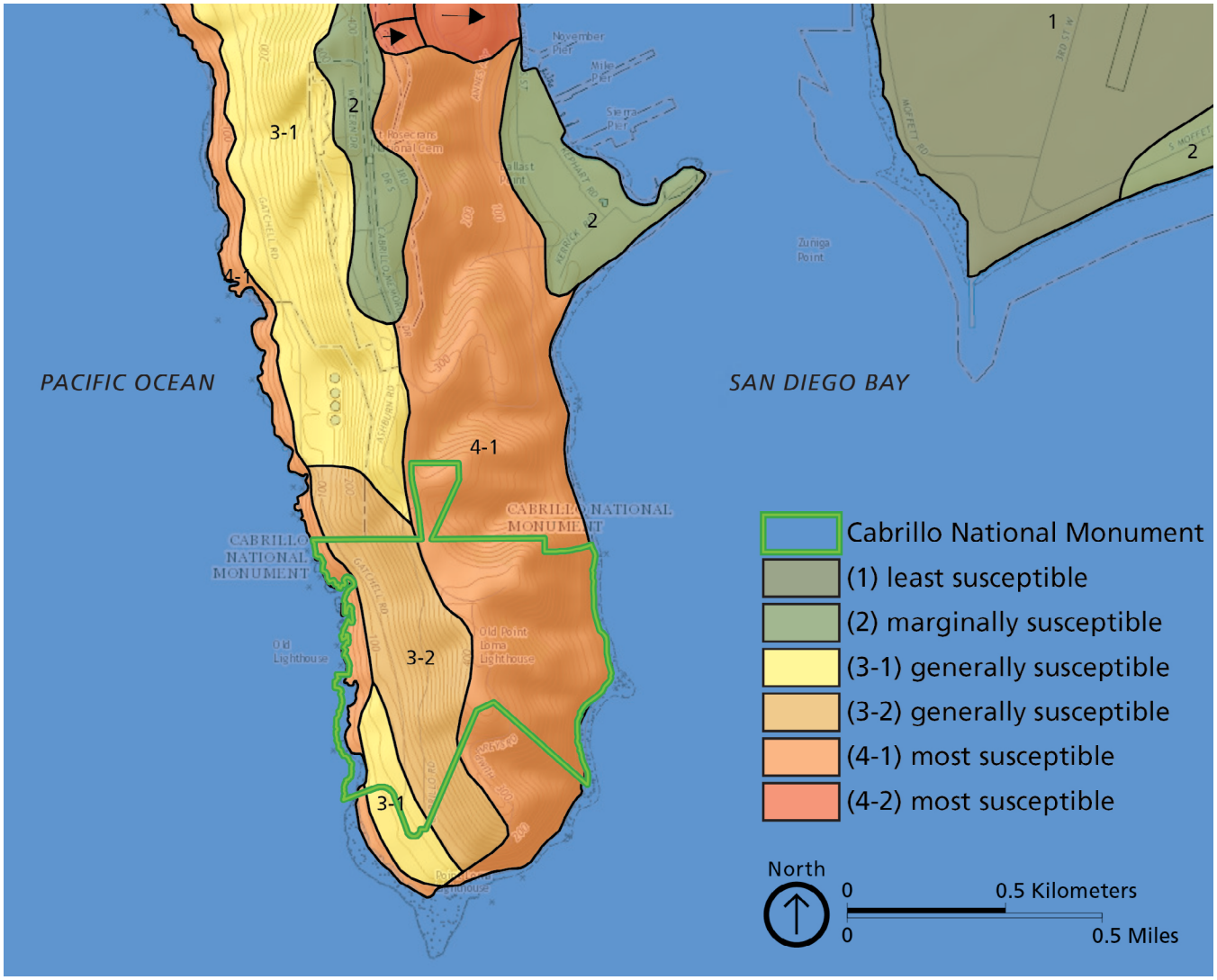


Figure 29. Map of landslide susceptibility.
As mapped by Tan (1995), the monument contains areas generally susceptible to landslides (Area 3) and most susceptible to landslides (Area 4). Subarea 3-1 has slopes that are at or near their stability limits due to a combination of weak materials and steep slopes (many slope angles exceed 15°). Although most slopes within Subarea 3-1 do not currently contain landslide deposits, they can be expected to fail, locally, when adversely modified. Subarea 3-2 generally occupies steeper and higher slopes that are less stable and more susceptible to landslides and other slope failures. Most slopes in subarea 3-2 have angles exceeding 25° and heights in excess of 80 m (250 ft). Debris flows and rockfalls may originate within Subarea 3-1 or 3-2 and flow downslope, sometimes at high enough speeds to catastrophically impact adjacent downslope land which may lie within areas 1, 2, 3, or 4. Land in Area 4 is characterized by unstable slopes and include all landslides shown on the maps (whether apparently active at present or not) and slopes with evidence of downslope creep of surface materials. Slopes within Area 4 should be considered naturally unstable, subject to failure even in the absence of anthropogenic activities. This category is subdivided into two subareas. Subarea 4-1, which covers the eastern half of the monument, is generally located outside the boundaries of definite mapped landslides but contains observably unstable slopes underlain by both weak materials and adverse geologic structure such as "dip slopes." It also includes questionable landslides and oversteepened high coastal bluffs which are subject to active wave erosion. Graphic by Jason Kenworthy (NPS Geologic Resources Division) using GRI GIS data (plhz_geology.mxd) derived from Tan (1995). Basemap is USGS National Map layer in ArcGIS (data derived from USGS The National Map: National Boundaries Dataset, National Elevation Dataset, Geographic Names Information System, National Hydrography Dataset, National Land Cover Database, National Structures Dataset, and National Transportation Dataset; US Census Bureau - TIGER/Line; and HERE Road Data).

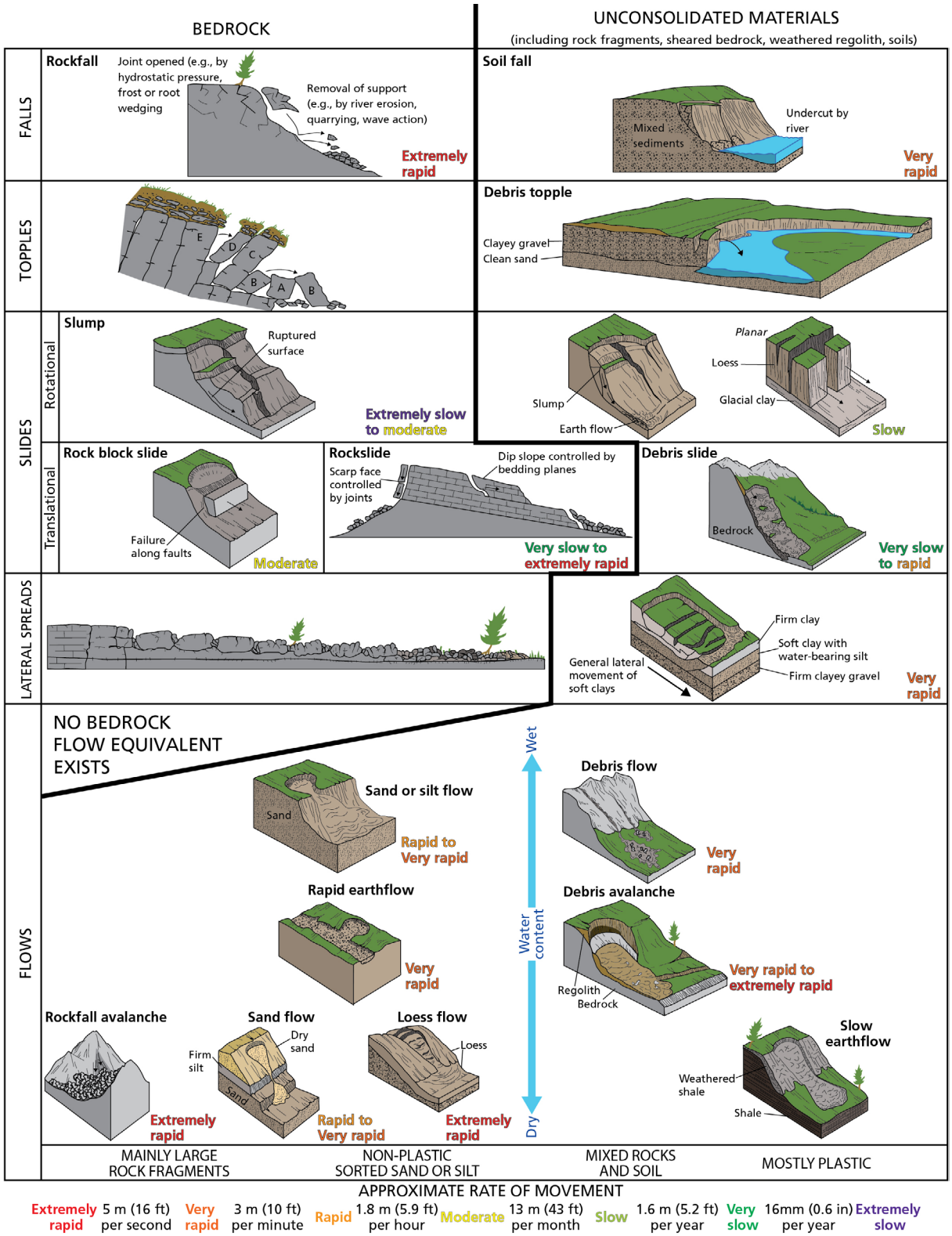


Figure 30. Graphic of slope movements.
Different types of slope movements are defined by material type, nature of the movement, rate of movement, and moisture content. Figure 29 discusses types of slope movements (e.g., debris flows and rockfalls) with the potential to occur in the monument. Graphic by Trista Thornberry-Ehrlich (Colorado State University) redrafted after a graphic and information in Varnes (1978). Rates of movement are from Cruden and Varnes (1996).

Figure 31. Photographs of landslides on Bayside Trail.
In 2005, landslides damaged two sections of the Bayside Trail. The arrow in the right photograph points to the landslide deposit; the surrounding eroded topography occurs in old paralic deposits. NPS photographs (Geologic Resources Division).

of the 20th century commonly did not take into account engineering geology (Kelly and May 2001). Construction disrupted and loosened soils, removed protective groundcover, and exposed large areas to massive erosion. Water seeps occur seasonally along the trail, in winter and spring following rainfall. Some plant species (e.g., ferns), either parallel to the trail or emerging from the cutbanks, are indicative of conditions where water is present for longer periods (Andrea Compton, Cabrillo National Monument, chief of Natural Resources Management and Science, written communication, 1 August 2008).

- Scoping participants made the following observations about slope movements at the monument (see KellerLynn 2008a):
- Although no landslide deposit in the monument was large enough to map at scale 1:100,000, landsliding is taking place locally. Some of the landslide deposits at the monument are fairly large and include both bedrock and surficial material. The closest mapped landslide deposit (**Qls**) is directly south of the monument at the eastern tip of Point Loma (see poster, in pocket).
- Besides landslides, other slope movements include slumps and soil creep; movement also takes place in unstable artificial fill.
- Although no colluvium (**Qyc**) deposit in the monument was large enough to be mapped by Kennedy and Tan (2008; scale 1:100,000), colluvium accumulates at the base of road cuts and near the scarps of old landslides. Multiple episodes of colluvium indicate repeated slope movement. The closest mapped colluvium is on the southern banks of the San Diego River and along La Jolla Mesa, north of the monument.
- Erosion and rapid deposition are associated with heavy rainfall events, which accelerate sediment movement and create rills (small channels), especially in artificial fill.
- Ephemeral streamflow has cut deep trenches into the upper slope profiles at the monument (see "Sea Cliffs, Sea Caves, and Other Coastal Features"); it also creates short-lived waterfalls.

The following resources may aid land-use planning at the monument with respect to slope movements:

The Landslide Handbook—A Guide to Understanding Landslides by Highland and Bobrowsky (2008) provides basic information about landslides (what they are, where they occur, what causes them, effects and consequences of landslides, and the interrelationship between landslides and other natural hazards), evaluating and communicating landslide hazards, and mitigation of landslides.

The chapter by Wieczorek and Snyder (2009) in *Geological Monitoring* describes vital signs for 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.

Websites by the US Geological Survey, NPS Geologic Resources Division, and California Geological Survey provide detailed information regarding landslides,

monitoring, and mitigation options (see "Additional References").

Resource managers could consider obtaining quantitative information to determine the frequency and magnitude of landslides and cliff failure in the "most susceptible" areas or other areas of concern. One possibility of acquiring such data is through a photomonitoring program. The NPS Geologic Resources Division Photogrammetry website (http://go.nps.gov/grd_photogrammetry) provides examples of how photographic techniques can support analysis of landslide areas. Another possibility is to acquire satellite imagery for use in geomorphic analysis of landslides. Many "virtual globes" (e.g., Google Earth), featuring high-resolution, multi-date, satellite imagery are now publicly available. DigitalGlobe (https://www.digitalglobe.com/) is a handy resource for sub-daily satellite imagery with resolution of less than 0.5 m (2 ft) (Matt Thomas, US Geological Survey, research hydrologist, written communication, 17 May 2017). As of June 2017, the National Park Service did not have access to DigitalGlobe imagery, but the US Geological Survey and Department of Defense (DOD) do. Partnering with DOD neighbors through the Point Loma Ecological Conservation Area (PLECA) may be an option for monument staff.

Earthquakes

Earthquakes are ground vibrations that occur when rocks suddenly move along a fault (see "Faults") releasing accumulated energy (Braile 2009). Earthquakes can directly damage park infrastructure or trigger other hazards, such as landslides (see "Sea Cliff Erosion" and "Slope Hazards"), which may impact park resources, infrastructure, or visitor safety.

The primary seismic hazard in the San Diego area appears to be from the Rose Canyon fault and nearby offshore faults such as the Coronado Bank fault (Reichle et al. 1990) (fig. 18). Earthquakes along the Rose Canyon fault zone have a maximum estimated magnitude (M) of 6.9 (Petersen et al. 1996).

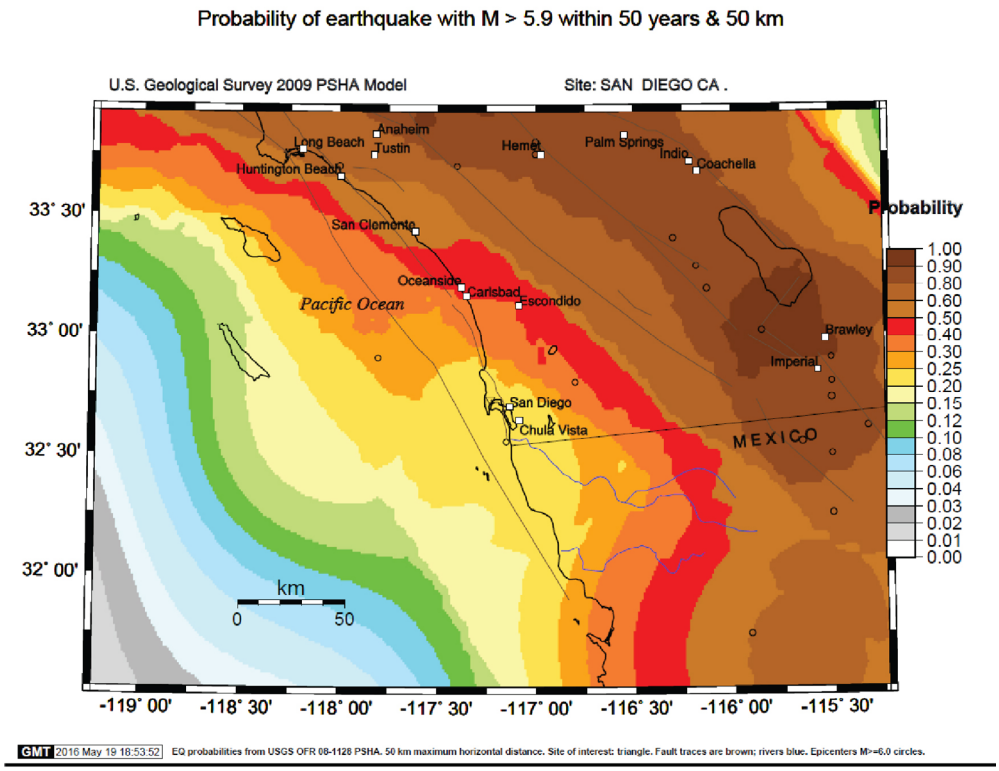
The magnitude of an earthquake is measured on a seismograph and represents the amount of energy released. The magnitude scale is logarithmic. For example, a M 6.9 earthquake is 10 times bigger than a M 5.9 earthquake—which was the magnitude of the last moderately large earthquake in San Diego (see discussion below)—and is about 32 times stronger in terms of the energy released. The US Geological Survey provides a calculator of earthquake magnitude at http://earthquake.usgs.gov/learn/topics/calculator.php.

A M 6.9 earthquake has a 0.04–0.06 probability (4%–6% "chance") of occurring in the vicinity of the monument in the next 50 years (fig. 32). A M 5.9 earthquake, similar the one in 1862 (see description below), has a 0.20–0.25 probability (20%–25% "chance") of occurring over that same time period (fig. 32) (US Geological Survey 2017a).

Seismic intensity is the felt effect of an earthquake at a particular place, for example, on buildings and furnishings, whether the earthquake was felt by humans, and, on some scales, whether animals appeared agitated. The determination of seismic intensity is therefore subjective. Many intensity scales have appeared during the last century (Barosh 1969), but the Modified Mercalli Intensity Scale (I–XII, indicating "not felt" to "damage total") is the most commonly used.

The US Geological Survey tracks earthquakes worldwide and reports them online at https://earthquake.usgs.gov/earthquakes/map/. The survey has started to collect "did you feel it" (DYFI) data at https://earthquake.usgs.gov/data/dyfi/. Commonly, people feel earthquakes with intensities of II or III, which corresponds to M 3.0–M 3.9 earthquakes.

The effects of past earthquakes can provide an understanding of what to expect from a future earthquake. The main shock of the last moderately large earthquake to strike San Diego (27 May 1862) occurred at about noon. Based on descriptions given at that time, Legg and Agnew (1979) estimated that this earthquake had an intensity VI to VII on the Modified Mercalli Scale, which correlates to a M 5.0–M 5.9 earthquake (US Geological Survey 2017b). Accounts say that two shocks were separated by some minutes, the second being stronger. In San Diego (the present Old Town) this shock stopped clocks and upset bottles and tumblers so that "many sets of crockery were demolished" (Legg and Agnew 1979, p. 139). The bell at the Army depot was set ringing. Apparently no one was injured, and no buildings were destroyed. However, many accounts mentioned damage to buildings, primarily cracking. Notably, most buildings in San Diego at that time were either adobe or poor masonry. Of significance for the monument, the lighthouse tower was not thrown out of adjustment and no glass was broken in it. At La Playa (on Point Loma), cracks formed on the beach, water came out of the sand on the tidal flats, and a piling that had just been driven into the mud was shaken loose. Some bluff banks on the eastern side of Point Loma collapsed. Several accounts mention cracks in low ground near the San Diego River, which washed over its banks.



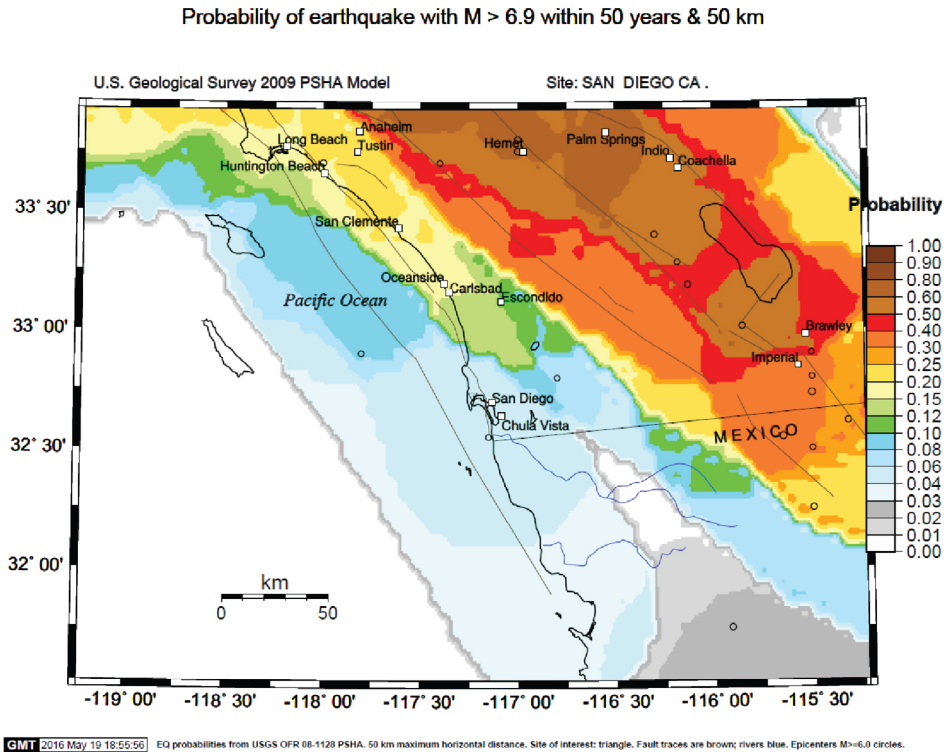


Figure 32. Maps of earthquake probability.
The top graphic shows the probability of a magnitude 5.9 (M 5.9) earthquake occurring within 50 years and 50 km (30 mi) of Cabrillo National Monument. The 1862 San Diego earthquake was an estimated M 5.9. The bottom graphic shows the probability of a M 6.9 earthquake occurring. The maximum earthquake on the Rose Canyon fault zone is an estimated M 6.9. Graphics generated using USGS Probabilistic Seismic Hazards Assessment (PSHA) online mapping tool (http://geohazards.usgs.gov/eqprob/2009/index.php; accessed 31 January 2017).

Planning Scenario

Planning scenarios—for example, the planning scenario for a major earthquake in the San Diego–Tijuana metropolitan area (Reichle et al. 1990), the ShakeOut scenario (Jones et al. 2008), and the HAZUS scenario and annualized earthquake loss estimation for California (Chen et al. 2011)—provide detailed information about earthquake risk. Risk is the likelihood of a hazard causing losses and is a combination of the probability of a hazard occurring and the value of assets in harm's way (Holmes et al. 2013). A hazard is a dangerous process, phenomenon, substance, activity, or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage (Holmes et al. 2013).

Reichle et al. (1990) completed a planning scenario for an earthquake that would rupture the entire Silver Strand fault, which is part of the Rose Canyon fault zone. That scenario is applicable for earthquake planning at the monument (Pam Irvine, California Geological Survey, senior engineering geologist, telephone and email communication, 15 June 2016). The Earthquake Engineering Research Institute, San Diego Chapter, is leading an effort to update the 1990 scenario (Earthquake Engineering and Research Institute 2016).

The Silver Strand fault extends approximately 39 km (24 mi) from downtown San Diego along the coast to the south, terminating about 26 km (16 mi) south of the international border. The length of a fault is significant because the longer the fault, the larger the potential earthquake can be (Wells and Coppersmith 1994). The Silver Strand fault was named for its proximity to the Silver Strand, which is a low, narrow, sandy isthmus 11 km (7 mi) long in on the western side of San Diego Bay (fig. 1). It connects Coronado Island with Imperial Beach. Together with the Point Loma peninsula, the Silver Strand shelters and defines San Diego Bay.

The planning scenario by Reichle et al. (1990) identified the following hazards. This planning scenario is based on the postulated occurrence of a M 6.8 earthquake on the Silver Strand fault south of downtown San Diego.

While this report was in final review, the US Geological Survey modeled a different earthquake scenario, a M 7.0 on the Rose Canyon Fault with an epicenter north of San Diego, east of La Jolla. Information about that scenario and associated maps and intensity projections are available at https://earthquake.usgs.gov/scenarios/eventpage/bssc2014rosecanyonshaw09modg_m6p99_se#executive. In short, the monument would experience shaking of Modified Mercalli Intensity VIII, the same value as determined by Riechle et al. (1990) as discussed below.

Fault Rupture

Fault rupture is a fracture in Earth's crust. If a rupture reaches the surface, built structures and lifelines (e.g., roads, fiber optic cables, petroleum and natural gas pipelines, railroads, aqueducts, and overhead electric power transmission lines) that straddle the fault will be sheared and offset.

Motion on the Silver Strand fault will be right-lateral, strike-slip with a maximum horizontal displacement of about 0.6 m (2 ft); vertical ground movements will be small. Reichle et al. (1990) concluded that the maximum horizontal displacement will most probably occur offshore with smaller surface displacements along the fault across the Silver Strand and in downtown San Diego. Effects of fault rupture onshore should be small. However, fault rupture could affect gas, water, or sewer lines where they cross the fault along the Silver Strand or in the downtown area.

Notably, the lack of a fault rupture hazard in the planning scenario by Reichle et al. (1990) resulted from a particular earthquake on the Silver Strand fault. More significant surface fault rupture onshore could be associated with a damaging event on another fault such as the Rose Canyon fault, and the effects on urban lifelines could be severe (Reichle et al. 1990).

Shaking

The sudden rupture of a fault produces shaking and it is these ground motions that are felt and that cause most of the damage. Reichle et al. (1990) concluded that potentially damaging shaking will continue for 10 to 15 seconds.

Although an earthquake has only one magnitude and epicenter, different locations will experience different shaking levels. The strongest shaking takes place very near the fault and dies off as seismic waves travel away. Natural basins filled with sediments trap some seismic waves and create pockets of stronger shaking with longer durations. Not every basin traps waves in every earthquake (Jones et al. 2008). The US Geological Survey provides "shakemaps" that show the area affected and intensities of shaking of earthquakes in California since 1971 (see http://earthquake.usgs.gov/earthquakes/shakemap/).

Reichle et al. (1990) found that areas of recent (Holocene) alluvium and artificial fill between the Tijuana River valley (California portion) and downtown San Diego/Coronado were subject to shaking of

Modified Mercalli Intensity IX (considerable damage to specially designed structures; great in substantial buildings with partial collapse; buildings shifted off foundations). They found that areas subject to shaking of Modified Mercalli Intensity VIII (considerable damage to ordinary substantial buildings; great in poorly built structures) extended from below Rosario, Mexico, to Del Mar, California, along the coast, and as far as 36 km (23 mi) inland for poorest ground conditions. Thus, Point Loma would be subject to shaking of Modified Mercalli Intensity VIII; however, intuition suggests that differences will occur in the area of Modified Mercalli Intensity VIII with respect to firmer ground, for example of Point Loma, and the more recent alluvial deposits and fill of Mission Bay and the areas bordering San Diego Bay (Reichle et al. 1990).

Liquefaction

Large earthquakes in southern California can trigger liquefaction (a phenomenon in which the strength and stiffness of sediment or soil is reduced by earthquake shaking). Coastal areas, the mouths of rivers, and artificial fill (**Qaf**; see GRI GIS data) commonly have conditions—loosely packed, water-logged sediments at or near the ground surface—that are susceptible to liquefaction. Reichle et al. (1990) found that liquefaction would be common in areas of hydraulic fill in Mission Bay, Loma Portal, and along the margins of San Diego Bay. Also, areas of recent alluvium, particularly along river channels, will experience moderate to severe liquefaction effects.

Landslides

Seismically induced landslides pose an additional possible threat where steep slopes exist (see "Slope Hazards"). Landslide problems will be greater during the rainy season than during the summer. Even though seismically induced landslides may not be pervasive in the San Diego metropolitan area, Reichle et al. (1990) recommended that the implications of landslides in some areas, including along Point Loma, should be considered in planning.

Aftershocks

Aftershocks are earthquakes and cause shaking and damage just like any other earthquake. Additional shaking caused by aftershocks can damage already weakened structures, necessitate evacuations, endanger rescue workers, and undo efforts to restore and rebuild. San Diego experienced frequent aftershocks in the weeks following the "mainshock" earthquake on 27 May 1862. Aftershocks were felt every day at San Diego until 8 June 1862—12 days after the first shock—and relatively frequently for the rest of June (Legg and Agnew 1979).

Tsunami

No tsunami (earthquake-generated wave) is anticipated by the planning scenario by Reichle et al. (1990). During the GRI scoping meeting in 2008, however, participants thought that the potential for tsunami seemed probable, though more information was needed in order to make a prediction and determine how much of San Diego would be inundated during a tsunami.

In 2009, the California Emergency Management Agency, California Geological Survey, and University of Southern California completed a tsunami inundation map of the Point Loma quadrangle (scale 1:24,000) for emergency planning (State of California, County of San Diego 2009). The map shows that a tsunami could impact the entire coastline of San Diego County, but only the southwestern corner of the Point Loma peninsula (i.e., the US Coast Guard Reservation) would be inundated (fig. 33). The inundation line on the map represents the maximum considered tsunami runup from a number of extreme, yet realistic, tsunami sources such as the Carlsbad thrust fault, Catalina fault, Coronado Bank fault, Lasuen Knoll fault, San Clemente fault bend region, and San Clemente Island fault. Due to a lack of known occurrences in the historical record, this map includes no information about the probability of any tsunami affecting any area within a specific period of time, though tsunamis are considered rare events in San Diego County (State of California, County of San Diego 2009).

Earthquake Risk Analysis and Monitoring

A risk analysis specific to the monument has not been conducted, but managers are encouraged to contact the NPS Geologic Resources Division with questions about earthquake risk. For example, GRD staff can conduct risk assessment of unstable slopes that could be triggered to fail during an earthquake. Many organizations provide information about risk and preparedness that would be useful for park planning (see "Additional References").

In the *Geological Monitoring* chapter about seismic monitoring, Braile (2009) described the following methods and vital signs: (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. "Additional References" provides more information and resources about earthquake hazards.

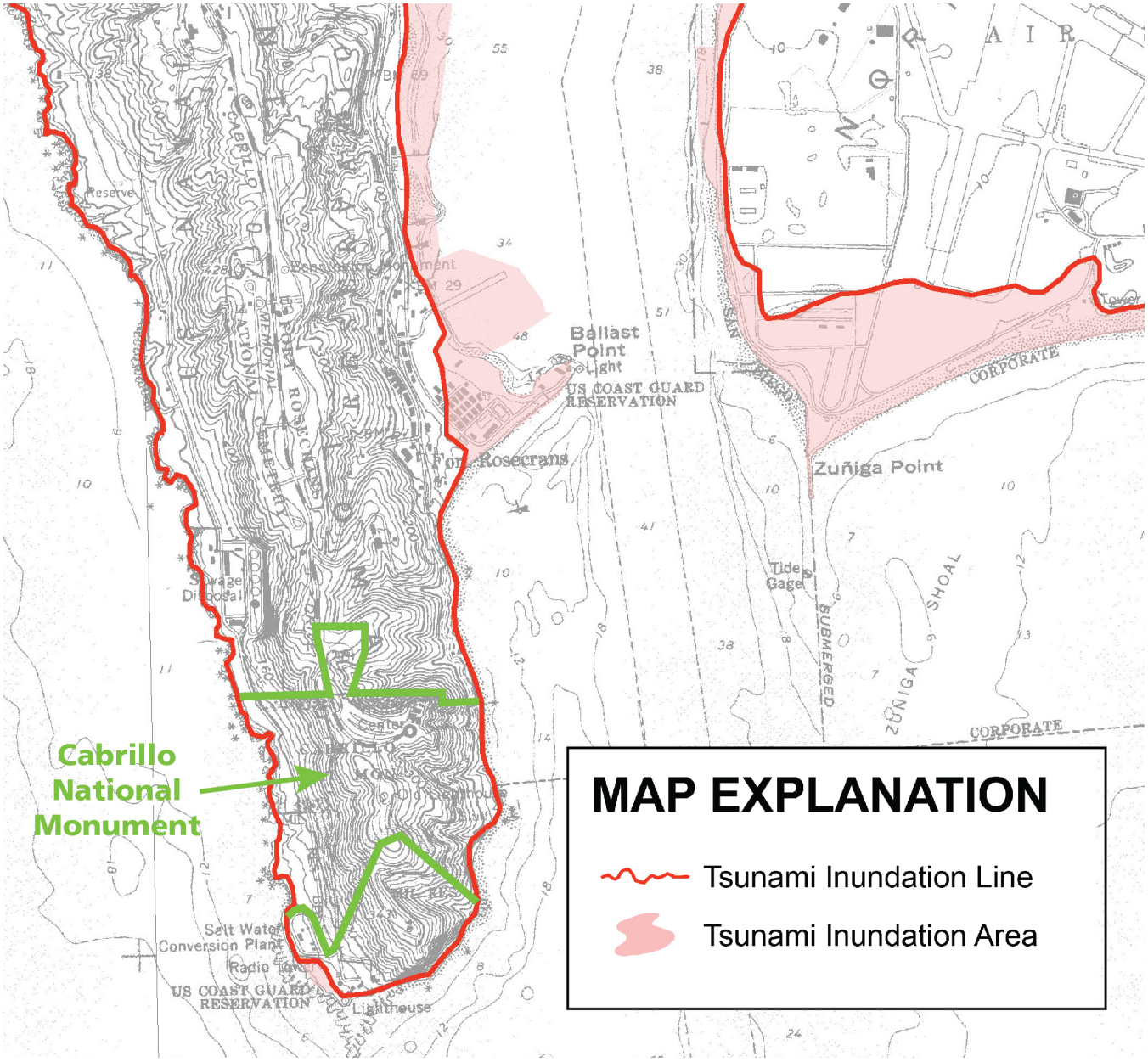


Figure 33. Map of tsunami inundation.
The graphic highlights a portion of the tsunami inundation map of the Point Loma quadrangle (scale 1:24,000). During such an event, the low-elevation, tip of Point Loma would be inundated. Park infrastructure is above the inundation line. Approximate park boundary indicated by green line. Graphic by Jason Kenworthy (NPS Geologic Resources Division) using State of California, County of San Diego (2009).

Monitoring the Physical Environment of Tidepools

The tidepools at the monument are subject to influences from myriad human activities associated with the large metropolitan area of San Diego, including harbor commerce, nearshore shipping of oil and other products, wastewater runoff and outfalls, onshore development, and direct disturbance or illegal collecting by beach explorers (Engle et al. 2000). As noted in the park guide, "survival of this marine habitat depends on the health of the surrounding ocean and land" (National Park Service 2007).

In order to gain information that will help to conserve the monument's tidepool communities, the National Park Service has been monitoring these communities through the Cabrillo Rocky Intertidal Monitoring

Program (CRIMP) since 1990. Engle and Davis (2000) documented ecological conditions and public use of the tidepools from 1990 to 1995, which indicated that seven of the 13 key intertidal species monitored had either declined or disappeared from the monument, five were considered stable, and one had increased. These findings alarmed monument managers and led to the enactment of the Tidepool Protection, Education, and Restoration Program (TPERP) in 1996. In 1997, CRIMP was incorporated into the Multi-Agency Rocky Intertidal Monitoring Network (MARINe), a regional collaborative effort that includes 23 federal, state, and local government agencies, universities, and private organizations throughout California (see http://www.marine.gov/About.html).

Since incorporation with MARINe, many changes have been made to the original CRIMP protocol to make it consistent with standardized MARINe protocols. Becker (2006) documented these changes and reported on the activities and results of CRIMP from 1990 to 2005, building on work by Engle and Davis (2000).

To date, monitoring at the monument has focused on key intertidal species, bird and visitor counts (i.e., few birds are found where there are many people while large numbers of birds are only found in the absence of large crowds), and human visitation. In the event that monument managers choose to monitor the physical environment of tidepools, the following vital signs may be of interest: (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. Bush (2009) described these vital signs in the *Geological Monitoring* chapter about marine features and processes.

Paleontological Resource Inventory, Monitoring, and Protection

Paleontological resources (fossils) are any evidence of life preserved in a geologic context (Santucci et al. 2009). As of March 2018, Cabrillo National Monument was one of 267 areas in the National Park System with paleontological resources. All paleontological resources are nonrenewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act (see Appendix B). As of March 2018, the regulations associated with the act are still being finalized. NPS policy-level guidance is provided in *Management Policies 2006* (section 4.8.2.1, paleontological resources and their contexts). In addition, Brunner et al. (2009) outlined NPS policy and perspectives for unauthorized fossil collecting from shorelines.

The monument's bedrock and paralic deposits contain fossils. Three NPS publications documented fossil resources at the monument: Koch and Santucci (2003), Tweet et al. (2012), and Tweet et al. (2014). Koch and Santucci (2003) completed a preliminary inventory of paleontological resources for the Mediterranean Coast Network, including Cabrillo National Monument. That report documented known fossils from the Upper Cretaceous Cabrillo and Point Loma Formations, and the Pleistocene Nestor terrace. Tweet et al. (2012, 2014) expanded on work conducted by Koch and Santucci (2003), compiling more information about the monument's fossils through extensive literature reviews and interviews with monument staff and professional geologists and paleontologists. Tweet et al. (2012, 2014) highlighted fossils types with the potential for discovery in the monument and the locations of significant specimens in museum collections.

A park-specific, field-based inventory has not been conducted in the monument. Such an inventory could provide detailed, site-specific descriptions and resource management recommendations that are beyond the scope of this report. The NPS Fossils and Paleontology website, https://www.nps.gov/subjects/fossils/index.htm, provides more information. Monument managers are encouraged to contact the Geologic Resources Division for assistance with a field-based inventory.

During scoping in 2008, participants identified erosion as a threat to the paleontological resources at the monument. Many fossils can be seen along the coast and in the tidepools. Constant coastal erosion can rapidly expose and destroy these fossils, presenting challenges to their management and protection.

In the *Geological Monitoring* chapter about paleontological resources, Santucci et al. (2009) described 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. These vital signs may be useful for addressing the threat of erosion on paleontological resources. Planning and monitoring for paleontological resources along the coastline of the monument should also consider the long-term impacts associated with sea level rise (Vincent L. Santucci, NPS Geologic Resources Division, senior paleontologist/GRD liaison, written communication, 10 January 2017).

Dredging

Point Loma forms the western side and entrance to San Diego Bay. The bay extends approximately 23 km (14 mi) along a curved axis from its entrance at Point Loma to its innermost reaches at the mouth of the Otay River in the south (fig. 1). The bay floor is naturally muddy or sandy and shallow. It consists of undivided marine deposits (**Qmo**).

The US Navy has four bases with approximately 80 surface ships and submarines in the bay. The cities of San Diego, National City, Chula Vista, Coronado, and Imperial Beach surround the bay. In addition, several public marinas in the bay house yachts, sailboats, charter boats, and a commercial fishing fleet. Also, a commercial port and a shipyard are located in the interior of the bay.

The Unified Port of San Diego is a public benefit corporation and special government entity created in 1963 by an act of the California legislature. The Unified Port of San Diego manages San Diego harbor and administers the public lands along the bay. It also maintains a central navigation channel by dredging to accommodate relatively deep vessels such as container ships, cruise liners, and Navy vessels including submarines and aircraft carriers. The US Navy, US Coast Guard, commercial boat yards, and San Diego Gas & Electric also have carried out dredging projects over the last several decades (Engle and Largier 2006). Only 17%–18% of the original bay floor remains undisturbed by dredging or fill (US Department of Navy 1999).

Engle and Largier (2006) provided information about the recent history of dredging in San Diego Bay. Dredged material from the bay is disposed of in one of three ways: (1) when sand content is greater than 80%, the material is used for beach replenishment at Imperial Beach, which is located at the southern end of the bay; (2) when sand content is less than 80%, dredged material is dumped at sea at the US Army Corps of Engineers ocean disposal site LA-5, which is about 6 km (4 mi) from the western shore of Point Loma in the Pacific Ocean at the 100 fathom contour; and (3) dredged material is relocated within the bay to serve as artificial reefs. The third option is utilized less frequently than the other two.

The results of a multibeam sonar survey indicated that not all disposal material is located within the designated disposal area (LA-5). A total of 252 mounds were observed outside the disposal site, and many of these were elliptical, indicating that material was dumped while vessels were underway. Within LA-5, 10 mounds were observed covering approximately 54% of the area. The LA-5 site is located immediately offshore of an approximately 50-m- (16-ft-) high scarp; therefore, mounds illegally dumped shoreward of the site are much shallower than the intended site and more prone to resuspension (Scripps Institution of Oceanography 2004).

Dredging is a geologic resource management concern because creating and maintaining a navigation channel can affect the stability of adjacent shorelines, sediment transport, and currents (National Park Service 2011), as well as water turbidity. Dredging reduces the ongoing natural sand supply to the adjacent shoreline and other portions of the coast, resulting in the potential loss of beaches as protective features against shoreline and cliff erosion.

Ecological impacts may occur in the areas where sand is dredged and placed (Beavers et al. 2016). Dredged areas can fill with fine-grained sediment that is re-suspended during storm events, in turn impacting adjacent resources such as coral reefs. Moreover, dredged areas with fine-grained sediment typically host a different ecological community than the naturally occurring one. Sand disposal may cause burial of intertidal invertebrate communities (Atlantic States Marine Fisheries Commission 2002) and sedimentation of hardbottom reef structure (Lindeman and Snyder 1999) either by direct placement on reefs or as sediment is transported by nearshore waves and currents (Peek et al. 2016).

Dredging may also affect water quality. Desorption (release through pores or interstices) of pollutants from dredged material disposed at or near disposal site LA-5 is a main route through which pollutants may enter the coastal ocean in the general vicinity of the monument (Engle and Largier 2006). Although material destined for LA-5 is purportedly "clean," chemical analysis conducted on material slated for disposal there showed that dredge material contained a wide range of contaminants, including total organic carbon (TOC), cadmium, chromium, copper, lead, mercury, nickel, selenium, silver, zinc, petroleum hydrocarbons, chlordanes, dieldrin, DDT, PAHs, and PCBs (Steinberger et al. 2003). The transport of dredged material past Point Loma toward dredge disposal site LA-5 creates another opportunity for dredging operations to degrade water quality in the vicinity of the monument (Engle and Largier 2006).

National Park Service Beach Nourishment Guidance (Dallas et al. 2012) provides guidance for managers in parks where dredging is an issue. The *Coastal Adaptation Strategies Handbook* (Beavers et al. 2016) also provides guidance as does the NPS Coastal Geology website (http://go.nps.gov/grd_coastal).

Geologic History

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

The geologic history of Cabrillo National Monument is a story dominated by two geologic periods—the Late Cretaceous and the Quaternary. Between these two periods, a long hiatus marked by an unconformity took place.

Late Cretaceous Period (100 million–66 million years ago)

Between 76 million and 72 million years ago (Late Cretaceous Period), the monument's bedrock (fig. 34) formed as sand, mud, and gravel were transported by streams from the rising Peninsular Ranges to the east. This material was transported into the Pacific Ocean, creating a huge submarine fan (fig. 10) that was deposited in water as much as 1,000 m (3,300 ft) deep (Sliter 1979; Nilsen and Abbott 1981). The Point Loma peninsula, including the bedrock in the monument, is composed of this fan, which consists of the Point Loma (**Kp**) and Cabrillo (**Kcs** and **Kccg**) Formations. The Point Loma and Cabrillo Formations are part of the Rosario Group. Undivided rocks of the Rosario Group (**Kuo**) make up the offshore area on the western side of the monument (see "Cretaceous Rocks and Fossils").

Long Hiatus

Following formation of the submarine fan, the San Diego coastal margin underwent uplift and erosion, which caused a break in deposition, resulting in an "unconformity" between the rocks deposited in the Upper Cretaceous Period and the overlying Quaternary deposits in the monument. This unconformity covers nearly 70 million years (72 million–2.6 million years ago).

Elsewhere in the San Diego area, the unconformity covers a shorter period of time—only until the middle Eocene Epoch (between about 48 million and 38 million years ago)—when nine partially intertonguing middle and upper Eocene rock sequences composed of siltstone, sandstone, and conglomerate were deposited during several major transgressive-regressive cycles (episodes of sea level rise/shoreline retreat changing to sea level fall/shoreline advance) (see, for example, May et al. 1984). Though not recorded in the monument, the succession of Eocene rocks is more than 700 m (2,300 ft) thick and grades from east to west through nonmarine fan and dune deposits, lagoonal and nearshore beach and beach-bar deposits, to marine continental shelf deposits near the present-day coastline (Kennedy and Tan 2008). In the GRI GIS data, "**T**" map units up through the Pomerando Conglomerate (**Tp**) represent deposition during the Eocene Epoch.

After deposition of these Eocene rocks, the San Diego margin was again uplifted and eroded. Continental and shallow-water lagoonal sediments of the Otay Formation (**To;** see GRI GIS data) were deposited during the Oligocene Epoch (34 million–23 million years ago). These rocks do not occur in the monument but have produced an important fossil vertebrate fauna elsewhere in southern California (Vincent L. Santucci, NPS Geologic Resources Division, senior paleontologist/GRD liaison, written communication, 10 January 2017).

After deposition of the Otay Formation, the San Diego coastal margin underwent uplift and extensive erosion. The next major marine transgression did not occur until the Pliocene Epoch when the strata of the San Diego Formation ("**Ts**" map units) were deposited.

Quaternary Period (2.6 million–0 years ago)

Following deposition of the San Diego Formation and continuing today, the San Diego coastal margin has undergone relatively steady uplift during the Quaternary Period. During the last 2.6 million years, a series of continually evolving marine wave-cut platforms were carved and uplifted. These platforms were covered by nearshore marine, beach, estuarine, lagoonal, and continental dune sediments ("**Q**" map units in the GRI GIS data) that were deposited across a marine–nonmarine transition zone and along a coastal strandline (ephemeral line where land and water meet). The marine terraces, which are ubiquitous to the San Diego coastal region, consist of an abrasion platform and overlying deposits. Changes in sea level coupled with regional uplift gave rise to the preservation and/or obliteration of both the abrasion platforms and associated deposits (e.g., Lajoie et al. 1991; Kern and Rockwell 1992; Kern 1996a, 1996b). Three marine terraces occur in the monument as represented by very old (**Qvop**) and old (**Qop6** and **Qop7**) paralic deposits. These deposits are associated with the Linda Vista (855,000 years old), Nestor (120,000 years old), and Bird Rock (80,000 years old) terraces.

The offshore region east of the monument is covered by marine deposits (**Qmo**) composed mostly of very fine- to medium-grained sand and silt. These late Holocene deposits are notably younger than the seafloor on the west side of the monument, which is composed of Upper Cretaceous rocks (**Kuo**). Floods from the

San Diego and Tijuana Rivers continually transport sediment into the subsiding San Diego Bay, thus keeping the bay's floor "youthful" (Abbott 2011).

One of the youngest onshore map units in the GRI GIS data is landslide deposits (**Qls**). As a consequence of ongoing tectonic processes, many Pleistocene landslides were reactivated in part or entirely during late Holocene time (Kennedy and Tan 2008).

The beginning of the Holocene Epoch coincided with the arrival of humans to the area. People were present in the Carlsbad area north of the monument by the early Holocene Epoch (Rick and Erlandson 2000). Human history at the monument encompasses the native Kumeyaay people, who made Point Loma their home prior to European exploration. Subsequent Spanish Colonial presence, starting with Cabrillo, was followed by citizens of the Republic of Mexico and American whalers, and finally more than a century of US military and Coastal Survey activities (Kelly and May 2001; National Park Service 2007).

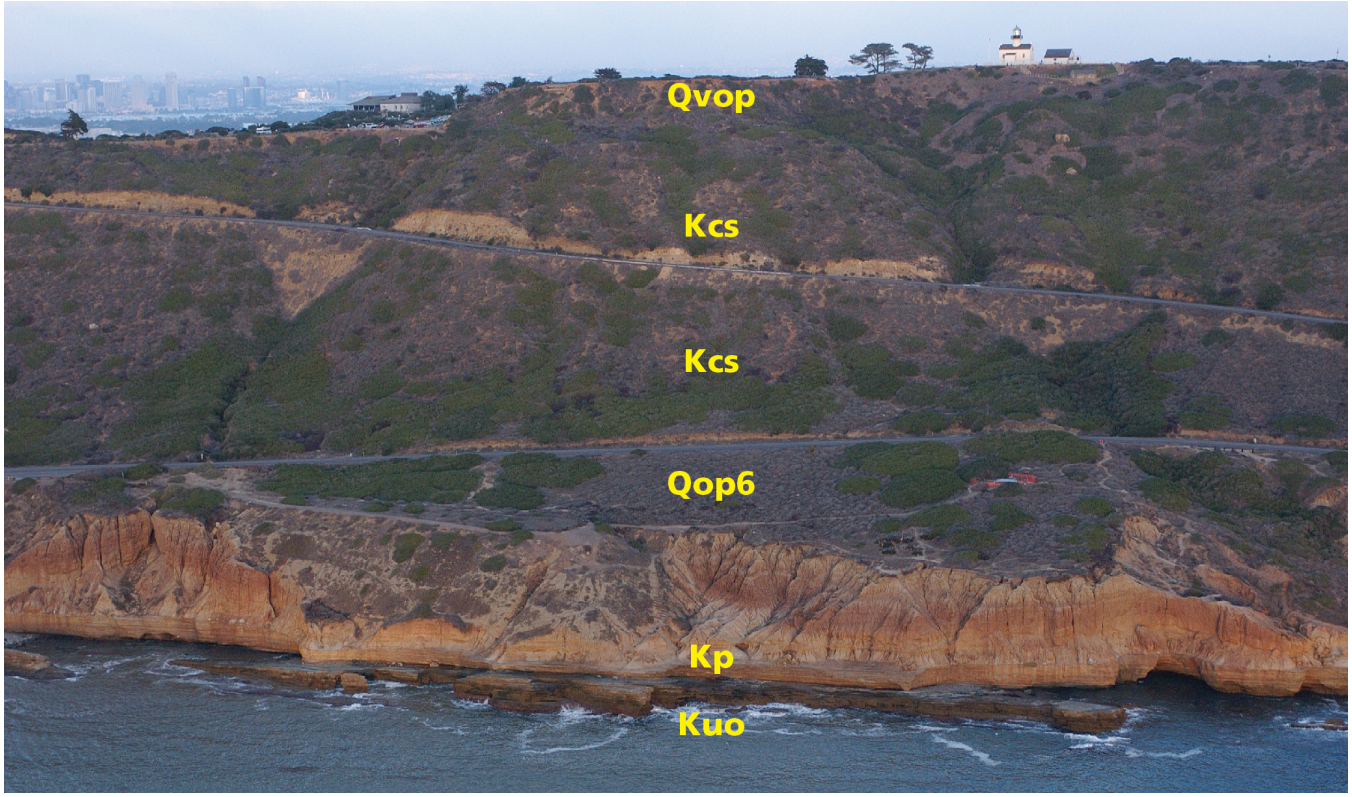


Figure 34. Photograph of bedrock and paralic deposits at Cabrillo National Monument. From bottom to top: Kuo = undivided rocks of the Rosario Group in the offshore area (Upper Cretaceous). Kp = Point Loma Formation (Upper Cretaceous). Qop6 = old paralic deposits, Unit 6 (middle to late Pleistocene); associated with the Nestor terrace. Kcs = Cabrillo Formation, sandstone (Upper Cretaceous). Cabrillo conglomerate (Kccg) is interbedded with sandstone (Kcs) and also crops out along the park road (see fig. 15). Qvop = very old paralic deposits, undivided (early to middle Pleistocene); associated with the Linda Vista terrace. California Coastal Records Project, Image 200407997, taken 23 October 2004. Copyright © 2002–2018 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.californiacoastline.org.

Geologic Map Data

A geologic map in GIS format is the principal deliverable of the GRI program. GRI GIS data produced for the monument follows the source maps listed here and includes components described in this chapter. A poster (in pocket) displays the data over imagery of the monument 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 (fig. 2) and lowercase letters indicating the formation's name. Other map 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 generally one of two types: surficial or bedrock. Surficial geologic maps typically 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, typically more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type. The GRI GIS data for Cabrillo National Monument include both bedrock and surficial information. The GRI GIS data include essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, cross sections, figures, and references.

Source Maps

The GRI team used three source maps to produce the GRI GIS data for the monument. Kennedy and Tan (2008) may be interpreted as the primary geologic map for the monument. It includes offshore geology. Data from Kennedy and Tan (2008) was compiled as the GRI GIS data set cabr_geology.mxd. A portion of these data are shown on the poster (in pocket). The GRI GIS data also include Kennedy (1975), which shows the geology of the Point Loma quadrangle at a scale of 1:24,000. It does not include offshore geology. Kennedy (1975) was compiled as the GRI GIS data set polm_geology.mxd. Interpretations and mapping by Kennedy and Tan (2008) superseded mapping by Kennedy (1975).

In addition, the GRI GIS data include Tan (1995), which shows the distribution and areas susceptible to landslides. Tan (1995) was compiled as the GRI GIS data set plhz_geology.mxd.

GRI GIS Data

The GRI team standardizes map deliverables by using a data model. The GRI GIS data for Park Name 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) data store portal https://irma.nps.gov/DataStore/Search/Quick. Enter "GRI" as the search text and select a park from the unit list.

The following components are part of the GRI GIS data:

- A GIS readme file (cabr_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 (see tables 3, 4, and 5);
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information document (cabr_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross sections, and figures; and

- ESRI map documents (cabr_geology.mxd [Kennedy and Tan 2008], polm_geology.mxd [Kennedy 1975], plhz_geology.mxd [Tan 1995]) that display the GRI GIS data.

Table 3. GRI GIS data layers for Cabrillo National Monument and vicinity (cabr_geology.mxd).

Note: cabr_geology.mxd is derived from Kennedy and Tan (2008).

Data Layer	On Poster?
Geologic Attitude and Observation Localities	No
Observed Transport Lines (general direction of transport of deposits)	None in monument
Hazard Features Lines (landslide, slump, and creep direction)	None in monument
Geologic Line Features (escarpments)	None in monument
Map Symbology	Yes
Folds	Yes
Faults	Yes
Deformation Area Boundaries	None in monument
Deformation Areas (fault zone)	None in monument
Geologic Contacts	Yes
Geologic Units	Yes

Table 4. GRI GIS data layers for Point Loma 7.5′ quadrangle (geology) (polm_geology.mxd).

Note: polm_geology.mxd is derived from Kennedy (1975).

Data Layer
Geologic Cross Section Lines
Geologic Attitude and Observation Localities
Map Symbology
Geologic Sample Localities (ages)
Geologic Point Features
Hazard Feature Lines
Folds
Faults
Geologic Contacts
Geologic Units

Table 5. GRI GIS data layers for Point Loma 7.5′ quadrangle (landslide susceptibility) (plhz_geology.mxd).

Note: plhz_geology.mxd is derived from Tan (1995).

Data Layer	On Fig. 29?
Hazard Feature Lines (landslide direction)	Yes
Landslide Susceptibility Areas Boundaries	Yes
Landslide Susceptibility Areas	Yes

GRI Map Poster

A poster of the GRI GIS data draped over a shaded relief image of the monument and surrounding area is included with this report. This poster highlights the source map by Kennedy and Tan (2008, scale 1:100,000), which is dataset cabr_geology.mxd. Not all GIS feature classes are included on the poster (table 3). 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 the GRI team 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 (1:100,000 and 1:24,000) and US National Map Accuracy Standards, geologic features represented in cabr_geology.mxd (source map by Kennedy and Tan 2008; scale 1:100,000) and on the poster are horizontally within 51 m (167 ft) of their true locations. They are within 12 m (40 ft) of their true locations on the Point Loma 7.5' quadrangle (scale 1:24,000), including polm_geology.mxd (source map by Kennedy 1975) and plhz_geology.mxd (source map by Tan 1995).

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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.

Climate Change Resources

- NPS Climate Change Response Program Resources: http://www.nps.gov/subjects/climatechange/resources.htm
- US Global Change Research Program: http://globalchange.gov/home
- Intergovernmental Panel on Climate Change (IPCC): http://www.ipcc.ch/ and http://www.climatechange2013.org/report
- US Army Corps of Engineers (USACE) sea level calculator: http://www.corpsclimate.us/ccaceslcurves.cfm
- NOAA tides and currents: http://www.tidesandcurrents.noaa.gov/sltrends/
- NPS storm surge mapping: http://mariacaffrey.com/storms
- NOAA historical storm data: http://www.ncdc.noaa.gov/ibtracs/. Note: A copy of these data are stored and maintained as a GIS database by the NPS Geologic Resources Division.

Coastal and Marine Resources

- California Seafloor Mapping Project: http://www.opc.ca.gov/2010/03/mapping-californias-seafloor-2/
- California Coastal Commission, Federal Consistency Unit (implements the federal Coastal Zone Management Act of 1972): https://www.coastal.ca.gov/fedcd/fedcndx.html
- California Coastal Sediment Management Workgroup: http://www.dbw.ca.gov/csmw/ Note: Provides links to spatial data, including beach profiles and coastal armoring.
- NPS Water Resources Division, Ocean and Coastal Resources Branch: https://www.nps.gov/orgs/1439/ocrb.htm Note: Provides information about servicewide programs, as well as resources and resource management programs at ocean, coastal, and Great Lakes parks. Shoreline maps of each park, along with shoreline and water acreage statistics from Curdts (2011), are available at http://go.nps.gov/shorelinemaps.
- NPS Geologic Resources Division Coastal Geology website: http://go.nps.gov/grd_coastal Note: Provides information about coastal hazards, climate change, human impacts, and research.

Earthquake Hazard Information

- California Geological Survey: http://www.conservation.ca.gov/cgs/geologic_hazards/earthquakes/Pages/index.aspx Note: Provides fault maps, historic earthquakes, how the ground is expected to shake, and much more.
- California Geological Survey earthquake shaking potential map (2008): http://www.conservation.ca.gov/cgs/information/publications/ms/Documents/MS48_revised.pdf
- California Geological Survey seismic hazards maps: http://maps.conservation.ca.gov/cgs/informationwarehouse/index.html
- California Geological Survey fault activity map: http://www.conservation.ca.gov/cgs/cgs_history/Pages/2010_faultmap.aspx (zoom in for the park area or other areas within the state) or http://maps.conservation.ca.gov/cgs/fam/
- California Geological Survey HAZUS scenario and annualized earthquake loss estimation (Special Report 222; Chen et al. 2011): ftp://ftp.consrv.ca.gov/pub/dmg/rgmp/2011%20Annualized%20Losses/CGS_SR222_%20Losses_Final.pdf
- California Office of Emergency Services (for discovering the hazards that exist in an area and how to reduce risk): http://myhazards.caloes.ca.gov/
- Earthquake Country Alliance (a centralized website of earthquake hazards and preparedness in California): http://www.earthquakecountry.org/
- Earthquake Country Alliance, ShakeOut scenario: http://www.shakeout.org/california/scenario/
- NPS Geologic Resources Division seismic monitoring information: http://go.nps.gov/geomonitoring
- Southern California Earthquake Center (provides forecast of California earthquakes): http://www.scec.org/ucerf
- Southern California Earthquake Data Center (operates at the Seismological Laboratory at Caltech and is the primary archive of seismological data for southern California), significant earthquakes and faults: http://scedc.caltech.edu/significant/fault-index.html
- US Geological Survey, California earthquake information: http://earthquake.usgs.gov/earthquakes/states/index.php?regionID=5
- US Geological Survey, ShakeMaps: http://earthquake.usgs.gov/earthquakes/shakemap/

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/

Geology of National Park Service Areas

- NPS Geologic Resources Division—Energy and Minerals; Active Processes and Hazards; Geologic Heritage: https://www.nps.gov/orgs/1088/index.htm
- NPS Geologic Resources Inventory: https://www.nps.gov/subjects/geology/gri.htm
- NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program: https://www.nps.gov/subjects/geoscientistsinparks/index.htm
- NPS Views (geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a variety of geologic parks):

Landslide Resources

- US Geological Survey: http://landslides.usgs.gov/
- NPS Geologic Resources Division: http://go.nps.gov/geohazards and http://go.nps.gov/geomonitoring (refer to "Slope Movements" chapter)
- California Geological Survey: http://www.conservation.ca.gov/cgs/geologic_hazards/landslides/Pages/LandslideTypes.aspx

NPS Resource Management Guidance and Documents

- 1998 National Parks Omnibus Management Act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf
- 2006 Management Policies (Chapter 4: Natural Resource Management): http://www.nps.gov/policy/mp/policies.html
- NPS-75: Natural Resource Inventory and Monitoring guideline: https://irma.nps.gov/DataStore/Reference/Profile/622933
- NPS Natural Resource Management Reference Manual #77: http://www.nature.nps.gov/Rm77/
- Geologic Monitoring manual: http://go.nps.gov/geomonitoring
- NPS Technical Information Center (TIC) (repository for technical documents): http://www.nps.gov/dsc/technicalinfocenter.htm

Tsunami Information

- California Geological Survey tsunami information; http://www.conservation.ca.gov/cgs/geologic_hazards/Tsunami/index.htm
- California Geological Survey tsunami maps: http://maps.conservation.ca.gov/cgs/informationwarehouse/index.html
  Note: Provides 1:24,000 maps for quadrangles covering the coastline of the monument.
- California Emergency Management Agency earthquake and tsunami hazards and mitigation information: http://hazardmitigation.calema.ca.gov/hazards/natural/seismic/hazards
- State of California Emergency Management Agency, Earthquake and Tsunami Program: http://www.oes.ca.gov/WebPage/oeswebsite.nsf/
- University of Southern California, Tsunami Research Center: http://www.usc.edu/dept/tsunamis/2005/index.php
- National Oceanic and Atmospheric Agency Center for Tsunami Research (MOST model): http://nctr.pmel.noaa.gov/time/background/models.html

US Geological Survey Reference Tools

- National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/
- Geologic Names Lexicon (Geolex; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html
- Geographic Names Information System (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/
- GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Find Maps")
- 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/

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting for Cabrillo National Monument, held on 6 May 2008, and/or the follow-up report writing conference call, held on 26 January 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.

Table A1. 2008 Scoping Meeting Participants.

Notes: 1=Led geology field trip in Cabrillo National Monument on 8 August 2008 in conjunction with ESRI International User Conference in San Diego; 2=Participated in Abbott field trip and GRI scoping meeting; 3=Participated in Abbott field trip.

Name	Affiliation	Position
Pat Abbot (1)	San Diego State University	Professor Emeritus
Lane Cameron	Mediterranean Coast Network	Network Coordinator
Andrea Compton (2)	Cabrillo National Monument	Chief of Natural Resources Management and Science
Guy Cochrane	US Geological Survey	Geophysicist
Gary Davis	NPS (retired)	Science Advisor
Eugene Fritsche	California State University Northridge	Professor Emeritus
Bruce Heise	NPS Geologic Resources Division	GRE Program Coordinator/Geologist
Pamela Irvine	California Geological Survey	Senior Engineering Geologist
Katie KellerLynn	Colorado State University	Research Associate/Geologist
Greg Mack	Pacific West Region	Geologist
Jason Minch	Santa Barbara Museum of Natural History	Dibblee Map Editor
John Minch	Santa Barbara Museum of Natural History	Dibblee Map Editor
Scott Minor	US Geological Survey	Research Geologist
Dan Muhs	US Geological Survey	Geologist
Stephanie O'Meara (3)	Colorado State University	Research Associate
Tom Suchanek	US Geological Survey	Geologist
Buddy Schweig	US Geological Survey	Geologist
Randy Schumann	US Geological Survey	Research Geologist
Heather Stanton (3)	Colorado State University	Research Associate
Chris Wills	California Geological Survey	Senior Engineering Geologist

Table A2. 2016 Conference Call Participants.

Name	Affiliation	Position
Rebecca Beavers	NPS Geologic Resources Division	Coastal Geology & Coastal Adaptation to Climate Change Coordinator
Andrea Compton	Cabrillo National Monument	Acting Superintendent
Katie KellerLynn	Colorado State University	Research Associate/Geologist
Jason Kenworthy	NPS Geologic Resources Division	GRI Reports Coordinator/Geologist
Keith Lombardo	Cabrillo National Monument	Chief of Natural Resources
Jim Wood	NPS Geologic Resources Division	Geologic Heritage and Education Program Coordinator

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 January 2018. 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 canceled 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.
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. Regulations in association with **2009 PRPA** are being finalized (December 2017).	**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.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Rocks and 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 other-wise 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 re-sources…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.
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.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Mining Claims	**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 are-as. **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; re-quires validity examination prior to operations on unpatented claims; and confines operations to claim boundaries.
Nonfederal Oil and Gas	**NPS Organic Act, 54 USC § 100751 et seq**. authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). Individual Park Enabling Statutes: **16 USC § 230a** (Jean Lafitte NHP & Pres.) **16 USC §450kk** (Fort Union NM) **16 USC § 459d-3** (Padre Island NS) **16 USC § 459h-3** (Gulf Islands NS) **16 USC § 460ee** (Big South Fork NRRA) **16 USC § 460cc-2(i)** (Gateway NRA) **16 USC § 460m** (Ozark NSR) **16 USC§698c** (Big Thicket N Pres.) **16 USC §698f** (Big Cypress N Pres.) **The Oil Pollution Act of 1990** requires responsible parties to compensate the public for the natural resources damage caused by the Deepwater Horizon oil spill.	**36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart B ("9B")** requires the owners/operators of nonfederally owned oil and gas rights 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 • 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 and Gas, Salable Minerals, and Non-locatable 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. **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 re-sources and/or administration. **Exceptions**: Native American 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 USC §§ 2101-2108)**, all minerals are subject to lease and apply to Native American trust lands within NPS units. **Federal Coal Leasing Amendments Act of 1975, 30 USC § 201** does not authorize the BLM to issue leases for coal mining on any area of the national park system.	**36 CFR § 5.14** states prospecting, mining, and…leasing under the mineral leasing laws [is] prohibited in park areas except as authorized by law. **43 CFR Part 3160** governs onshore oil and gas operations, which are overseen by the BLM. BLM regulations at **43 CFR Parts 3100, 3400, and 3500** govern Federal mineral leasing. Regulations re: Native American Lands within NPS Units: **25 CFR Part 211** governs leasing of tribal lands for mineral development. **25 CFR Part 212** governs leasing of allotted lands for mineral development. **25 CFR Part 216** governs surface exploration, mining, and reclamation of lands during mineral development. **25 CFR Part 224** governs tribal energy resource agreements. **25 CFR Part 225** governs mineral agreements for the development of Indian-owned minerals entered into pursuant to the **Indian Mineral Development Act of 1982, Pub. L. No. 97-382, 96 Stat. 1938** (codified at **25 USC §§ 2101-2108**). **30 CFR §§ 1202.100-1202.101** governs royalties on oil produced from Indian leases. **30 CFR §§ 1202.550-1202.558** governs royalties on gas production from Indian leases. **30 CFR §§ 1206.50-1206.62 and §§ 1206.170-1206.176** governs product valuation for mineral resources produced from Indian oil and gas leases. **30 CFR § 1206.450** governs the valuation coal from Indian Tribal and Allotted leases.	**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** **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.	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**. **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.	**Section 8.7.3** states that operators exercising rights in a park unit must comply with **36 CFR Parts 1 and 5**.
Park Use of Sand and Gravel	**Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units. **Exception:** **16 USC §90c 1(b)** the non-wilderness portion of Lake Chelan National Recreation Area, where sand, rock and gravel may be made available for sale to the residents of Stehekin for local use as long as such 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 ● 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. **Coastal Wetlands Planning, Protection and Restoration Act ("Breaux Act", Public Law 101-646, Title III CWPPRA) (1990)** identifies, prepares, and funds construction of coastal wetlands restoration projects. **Coastal Barriers Resource Act 16 USC §§ 3501-3510 (2003)** restricts Federal expenditures that encourage development of coastal barriers and considers long-term conservation of natural resources. **Executive Order 11644 (use of off-road vehicles on public lands) (1972)** establishes policies to control and direct ORV use on public lands so as to protect land resources, promote safety of land users, and to minimize conflicts among land uses. **Executive Order 11989 (off-road vehicles on public lands) (1974)** closes off-road areas to ORV use that will impact soil, vegetation, wildlife, wildlife habitat, or cultural or historic resources until adverse effects have been eliminated and measures have been implemented to prevent future recurrence. Also includes authority to close public lands to ORVs where their use is not specifically authorized. *continued in Regulations column*	**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 low-lands. **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. **36 CFR §4.10** prohibits motor vehicle use except on park roads, in parking areas and on routes and areas designated for off-road motor vehicle use; and requires that designated ORV routes and areas be promulgated as special regulations, with designations complying with Executive Order 11644. *Laws, continued:* **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 listing*	**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 ● Avoid putting new developments in areas subject to natural shoreline processes unless certain factors are present. *See also Climate Change listing*

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 in-corporate 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). **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. **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). *Guidance, continued:* **NPS Climate Change Response Strategy (2010)** describes goals and objectives to guide NPS actions under four integrated components: science, adaptation, mitigation, and communication. **Revisiting Leopold: Resource Stewardship in the National Parks (2012)** will guide US National Park natural and cultural re-source 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. *continued from 2006 Management Policies column:* **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 land-scape 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 ● develop/follow written prescriptions (instructions).

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

NPS 342/146245, June 2018

National Park Service
U.S. Department of the Interior

Natural Resources Stewardship and Science
1201 Oak Ridge Drive, Suite 150
Fort Collins, Colorado 80525

https://www.nps.gov/nature/index.htm