National Park Service
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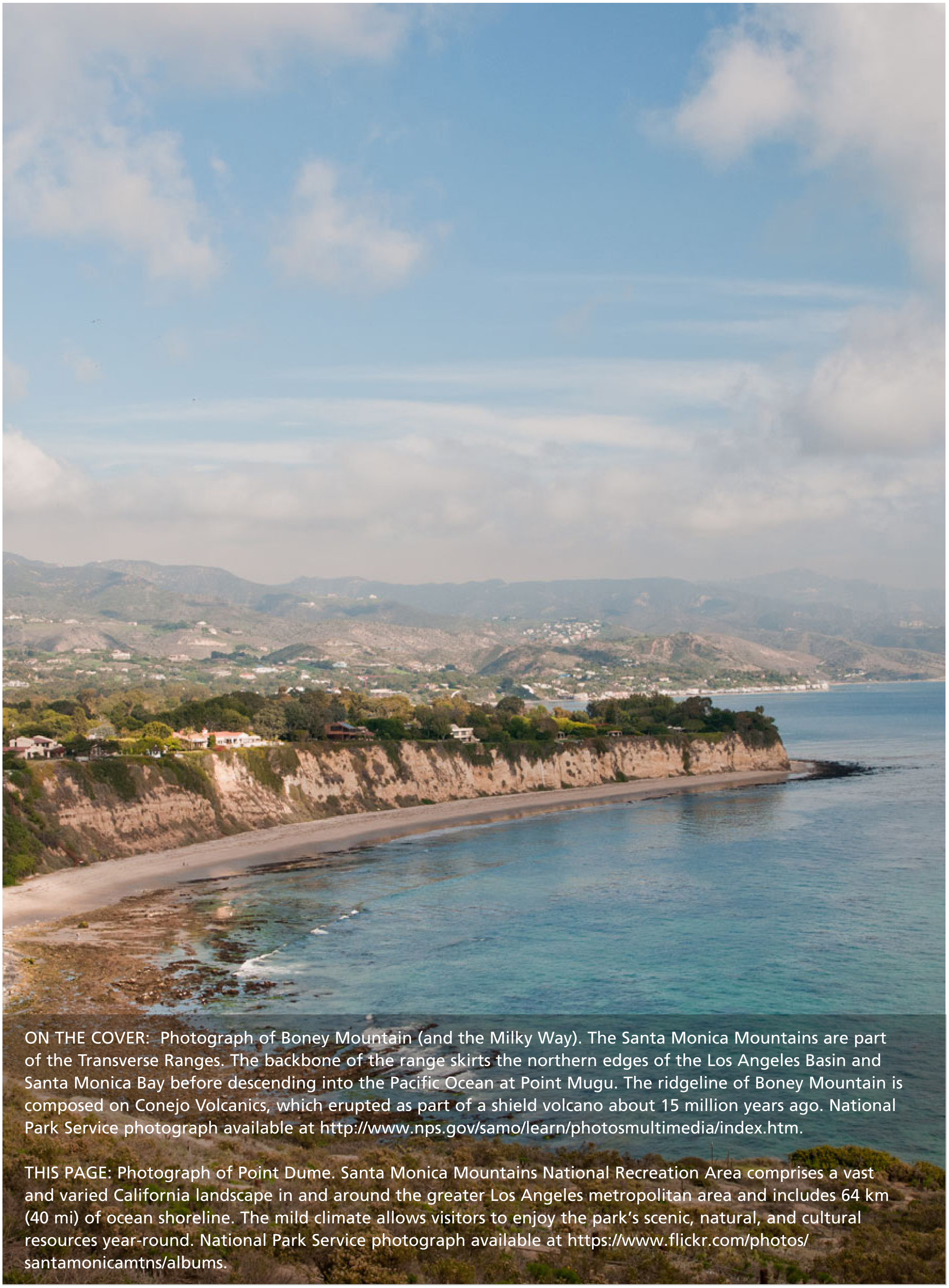
Natural Resource Stewardship and Science

Santa Monica Mountains National Recreation Area

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2016/1297



ON THE COVER: Photograph of Boney Mountain (and the Milky Way). The Santa Monica Mountains are part of the Transverse Ranges. The backbone of the range skirts the northern edges of the Los Angeles Basin and Santa Monica Bay before descending into the Pacific Ocean at Point Mugu. The ridgeline of Boney Mountain is composed on Conejo Volcanics, which erupted as part of a shield volcano about 15 million years ago. National Park Service photograph available at http://www.nps.gov/samo/learn/photosmultimedia/index.htm.

THIS PAGE: Photograph of Point Dume. Santa Monica Mountains National Recreation Area comprises a vast and varied California landscape in and around the greater Los Angeles metropolitan area and includes 64 km (40 mi) of ocean shoreline. The mild climate allows visitors to enjoy the park’s scenic, natural, and cultural resources year-round. National Park Service photograph available at https://www.flickr.com/photos/santamonicamtns/albums.

Santa Monica Mountains National Recreation Area

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2016/1297

Katie KellerLynn

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

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

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

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

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Executive Summary

The Geologic Resources Inventory (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 for Santa Monica Mountains National Recreation Area (California) in 2008 and a follow-up conference call in 2015, which were held by the NPS Geologic Resources Division to identify geologic resources of significance and geologic resource management issues, as well as determine the status of geologic mapping. It is a companion document to the GRI GIS data.

Literally and figuratively, Santa Monica Mountains National Recreation Area (referred to as the "park" throughout this report) rises out of the heart of Los Angeles. The park is at once an integral part of the city and a world apart. More than 18 million people live within an hour's drive of the park, which offers access to surprisingly wild places (National Park Service 2015a).

This GRI report was written for resource managers at the park to support science-informed decision making. It may also be useful for interpretation. This report addresses a fundamental resource and value—science-informed stewardship/learning laboratory—in which science guides park management, informs policy, and lays the groundwork for educating visitors and fostering stewardship (National Park Service 2015a). Sections of the report discuss distinctive geologic features and processes, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the GRI GIS data that accompany this report. This report was prepared using available geologic information. No new fieldwork was conducted in association with its preparation.

Mapping by the California Geological Survey (Wills et al. 2012; Campbell et al. 2014) served as the sources for the GRI GIS data that accompany this report. A poster (in pocket) illustrates these data. The GRI GIS data cover the area of the park and much of the densely populated urban and suburban areas of the southern California megalopolis. The GRI GIS data also contain mapping from a landslide inventory by Irvine and McCrink (2012).

Geologic features and processes that are significant for the park include the following. Landscape-scale features and processes are discussed before smaller scale features and processes.

- **Plate Boundaries**. The park's geologic features are the result of a complex history of plate-boundary evolution. The park is located at a modern transform plate boundary where the Pacific plate (large, rigid slab of oceanic crust) and North American plate (large, rigid slab of continental crust) are sliding horizontally past each other. The transform plate boundary is associated with the San Andreas Fault system. In the past, the margin of the continent was associated with a different type of plate boundary—a convergent plate boundary—where the oceanic Farallon plate was subducting beneath (diving under) the continental North American plate. During the transition from subduction to transform plate motion, a block of continental crust, referred to as the Western Transverse Ranges block, was caught in a zone of deformation at the plate boundary and rotated clockwise. In contrast to the generally north–south orientation of most of the other mountains in California, the east–west orientation of the Transverse Ranges, of which the Santa Monica Mountains are a part, illustrates this incredible episode of rotation in the evolution of the plate boundary.
- **Faults**. As recorded in the GRI GIS data, an estimated 1,040,089 m (3,412,365 ft or 646 mi) of fault segments cut through the park. The primary active faults in the Santa Monica Mountains area are the Malibu Coast Fault, which run both onshore and offshore, and the Anacapa-Dume Fault, which is offshore.
- **Folds**. Folded structures characterize the east–west-oriented Santa Monica Mountains. Compression, probably related to subduction of the Farallon plate below the North American plate, created a generally north–south-trending anticline ("A"-shaped fold) that is revealed in the uplifted Santa Monica Slate (the oldest rock in the park). Since

about 4 million years ago, when the San Andreas Fault system made its appearance on the landscape, many secondary northwest–southeast-trending anticlines and synclines ("U"-shaped folds) have been superimposed on the preexisting anticline.

- **Unconformities**. The rock record at the park represents approximately 156 million years of geologic time. During this time span, preexisting rocks were uplifted and deformed, resulting in the interruption of conformable (continuous) deposition and the creation of seven notable unconformities in the park's rock record.
- **Rock Types**. The park has all three major types of rocks. Most are sedimentary, though igneous (both extrusive and intrusive) and metamorphic rocks also occur.
- **Formations**. A "formation" is a distinctive layer or sequence of strata deposited in a comparatively short span of geologic time and identified by a proper name. Formations are the basic unit used in geologic mapping. The park contains 17 formally designated formations that were deposited from the Late Jurassic Period to the Miocene Epoch. Fourteen of these formations are sedimentary, two are igneous, and one is metamorphic.
- **Type Sections**. Type sections (reference localities) for eight formations occur within the authorized boundary of the park. Containing this many type sections is uncommon and notable for any single park. The number of type localities within the park is probably due to its complex tectonic history and position on an active plate boundary, which ensured that a wide variety of rock units were brought together and exposed.
- **Paleontological Resources**. The park contains one of the most extensive and diverse fossil records in the National Park System, yielding fossil vertebrates, invertebrates, plants, microfossils, and trace fossils from more than 2,300 known fossil localities. The most abundant fossils are invertebrates such as bivalves, cephalopods, and gastropods; the least abundant are plants. Fossil fish make up the majority of vertebrate material.
- **Landslides**. The park is located near the southern boundary of the Transverse Ranges, which compose a tectonically active area where uplift and extensive folding and faulting have produced many steep slopes consisting of deformed and weakened rocks. These conditions have resulted in the widespread occurrence of landslides; 2,503 landslides of various types were mapped by Irvine and McCrink (2012) within the park.
- **Fluvial Features**. Alluvium marks active, intermittent, and past streams. Malibu, Solstice, and Topanga creeks are perennial streams that flow in the park. Other streams have segments that are perennial.
- **Cave and Karst Resources**. Erosion has created small sandstone caves in the Chatsworth (**Kc**), Sespe (**Ts** and **Tsp**), and Topanga Canyon ("**Ttc**" map units) formations in the park. Continuous wave activity has created sea caves in rocky areas along the ocean front in the park. The "Bat Cave" of Batman and Robin fame, occurs in the park; it is not a natural cave but is significant for the park's film-making history. The Grotto, which appears to be a talus-style cave in the Conejo Volcanics ("**Tco**" map units), is a popular hiking destination at Circle X Ranch. The limestone—Santa Susana Formation (**Tss** and **Tssl**)—within the park does not exhibit characteristic karst features such as sinkholes, but karst processes still occur, such as those related to groundwater discharge and recharge.
- **Eolian Features and Processes**. Eolian deposits composed of loose, fine- to medium-grained sand, silty sand, and silt, form transitory dunes against beach-facing cliffs in the park. The "Great Dune," south of Point Mugu on the Pacific Coast Highway, is the park's most noteworthy eolian feature.
- **Marine and Coastal Resources**. The park's boundary stops at mean high water, so the National Park Service does not have any management obligations for marine resources. Deep, submarine canyons, such as Mugu and Hueneme, off the Santa Monica Mountains coastline are of interpretive interest, however. In addition, shipwrecks and kelp forests are notable submerged resources off the coast. The Santa Monica Mountains are known for sand and cobble beaches. Beach deposits are more-or-less continuous along the 64 km (40 mi) of coastline in the park. The authorized boundary also contains rocky intertidal areas with tide pools and coastal lagoons (e.g., Malibu, Topanga, and Zuma). Two prominent marine terraces—Malibu and Point Dume—occur in the Santa Monica Mountains area. The park contains young marine terrace deposits, but their relationship to the area's prominent marine terraces is unknown.

Geologic resource management issues identified during the GRI scoping meeting and follow-up conference call include the following. They are discussed in order of management priority. Park managers are encouraged to contact the NPS Geologic Resources Division for technical and/or policy assistance with these issues.

- **Landslide Hazards**. Landslides pose a significant threat to park infrastructure and human safety. The GRI GIS data show 3,580 landslide deposits ("hazard point/area features") that are part of a landslide inventory conducted by the California Geological Survey. This inventory, which is ongoing, revealed the extent of past movement and the probable locus of future activity. Many sources of park-specific landslide information are available for use by park managers.
- **Paleontological Resource Inventory, Monitoring, and Protection**. At least 2,300 known fossil localities occur in the park. A data and/or GIS need is to inventory these locations. Development of a resource stewardship strategy is also needed. As with all National Park Service areas, fossil collecting is prohibited in the park. However, this regulation may not be common knowledge, and with increasing recreational use comes an increased potential for illegal fossil collecting within the park. Researchers need to acquire permits for paleontological investigation and collection within the park. Illegal fossil collecting, natural erosion, and graffiti threaten the park's paleontological resources.
- **Climate Change Planning and Sea Level Rise**. Climate change, in conjunction with other stressors, will probably affect all aspects of park management from natural and cultural resources to park operations and visitor experience. Climate change will manifest itself not only as shifts in mean conditions (e.g., increasing mean annual temperature) but also as changes in climate variability (e.g., more intense storms and droughts). Sea level rise is a primary concern with respect to climate change. However, none of the 270 NPS "assets" (e.g., buildings, roads, trails, managed landscapes, or historic structures) in the park are actually situated on the coast, so they all have "limited exposure" to 1 meter of sea level rise. The National Park Service has developed a variety of databases and guidance for managing coastal resources and planning for the impacts of climate change.
- **Earthquakes**. Earthquakes can directly damage park infrastructure or trigger other hazards such as slope movements that may impact park resources, infrastructure, or visitor safety. A range of possible earthquake magnitudes has been estimated for the park. A magnitude 5.3 earthquake has a 0.8 to 0.9 probability (80%–90% "chance") of occurring within 50 km (30 mi) of the park in the next 50 years. A magnitude 6.7 earthquake has a 0.40–0.50 probability (40%–50% "chance") of occurring within 50 km (30 mi) of the park in the next 50 years. The primary hazard associated with earthquakes in the Santa Monica Mountains area is shaking produced by the sudden rupture of a fault; liquefaction, landslides, tsunami, and seiche are secondary hazards. The California Geological Survey and other agencies provide information for understanding earthquakes and preparing for them.
- **Cave and Karst Resource Management**. The significance of known cave and karst resources at the park is low, though the park does contain sandstone caves (inland) and sea caves (in rocky shoreline areas) that are in need of a comprehensive inventory.
- **Flooding and Dam Failure**. During the winter rainy season, streams overflow, flooding park infrastructure. During such events, parking lots have washed out. Floodwaters also threaten cultural resources at Peter Strauss Ranch. Most of the ponds in the park are stock ponds used for past ranching. Most natural ponds in the park have been dammed to increase their areas, resulting in the potential for dam failure and damage to downstream cultural resources. The estimated 10 largest reservoirs within the park do not belong to the National Park Service. The primary concern with these reservoirs is dam failure and damage to homes, infrastructure, and resources below.
- **Abandoned Mineral Lands and Other Disturbed Lands**. Compared to other mountain ranges in the area, very little historic prospecting took place in the Santa Monica Mountains. Nevertheless, mineral exploration resulted in a few World War II–vintage quarries in Santa Ynez Canyon (outside the park). Also, oil and gas exploration produced some dry holes on Point Dume. At present, the servicewide abandoned mineral lands (AML) database documents no AML sites or features from within the park. Future acquisition of lands by the National Park Service could result in potential

disturbances on NPS lands; for instance, lands in the Santa Susana Mountains, which are under consideration for inclusion, have a legacy of oil and gas production. Other non–AML disturbed lands in the park include Malibu Creek and the stream running through Solstice Canyon, which have been dammed; excessive sedimentation is an associated management issue with these creeks.

Products and Acknowledgments

The NPS Geologic Resources Division partners with institutions such as Colorado State University, the US Geological Survey, state geological surveys, local museums, and universities to develop GRI products. This section describes those products and acknowledges contributors to this report.

GRI Products

The objective of the Geologic Resources Inventory is to provide geologic map data and pertinent geologic information to support resource management and science-informed decision making in more than 270 natural resource parks throughout the National Park System. To realize this objective, the GRI team undertakes three tasks for each natural resource park: (1) conduct a scoping meeting and provide a summary document, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report (this document). These products are designed and written for nongeoscientists.

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

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

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

Acknowledgments

The GRI team thanks the participants of the 2008 scoping meeting and 2015 conference call (see Appendix A) for their assistance in this inventory. In particular, thanks very much to **Eugene Fritsche** (California State University, Northridge, Department of Geological Sciences, professor emeritus) for his PowerPoint presentation and the handouts he provided at the GRI scoping meeting. This information guided writing of the "Geologic History" and other sections of this report. Thanks to **Stephanie Kyriazis** (Santa Monica Mountains National Recreation Area, interpreter) for suggesting many references used in writing this report. Thanks to **Jim Chappell** (Colorado State University, geologist/GIS specialist) for his help in estimating the lengths of faults and folds in the GRI GIS data. Thanks to **Trista Thornberry-Ehrlich** (Colorado State University, research associate) for her assistance in creating many of the graphics used in this report. Thanks to **Susan Jordan**, **Kenneth Adelman**, and **Gabrielle Adelman** (California Coastal Records Project) for permission to use their photographs. Finally, thanks very much to **Pam Irvine** (California Geological Survey, senior engineering geologist) for reviewing this report. Her guidance on the park's geologic history was particularly helpful, and her input and perseverance are much appreciated.

Review

Pam Irvine (California Geological Survey)
Denise Kamradt (Santa Monica Mountains National Recreation Area)
Jason Kenworthy (NPS Geologic Resources Division)
Dale Pate (NPS Geologic Resources Division)
Vincent Santucci (NPS Geologic Resources Division)
Justin Tweet (NPS Geologic Resources Division)
Chris Wills (California Geological Survey)

Editing

Rebecca Port (NPS Geologic Resources Division)

Report Formatting and Distribution

Jason Kenworthy (NPS Geologic Resources Division)
Rebecca Port (NPS Geologic Resources Division)

Source Maps
California Geological Survey
US Geological Survey

GRI Digital Geologic Data Production
James Winter (Colorado State University)
Stephanie O'Meara (Colorado State University)
Andrea Croskrey (NPS Geologic Resources Division)

GRI Poster Design
Chase Winters (Colorado State University)

GRI Poster Editing
Georgia Hybels (Colorado State University)
Rebecca Port (NPS Geologic Resources Division)
Jason Kenworthy (NPS Geologic Resources Division)

Geologic Setting and Significance

This section describes the regional geologic setting of Santa Monica Mountains National Recreation Area and summarizes connections among geologic resources, other park resources, and park stories.

Adjacent to Los Angeles—the second largest urban area in the United States—Santa Monica Mountains National Recreation Area, referred to as the "park" throughout this report (fig. 1, in pocket), boasts five area codes and 26 zip codes, including the notable 90210 of Beverly Hills (National Park Service 2015b). Extending from Point Mugu to downtown Los Angeles, the rugged landscape and geologic features of the Santa Monica Mountains serve as an urban refuge and offer a variety of exceptional vistas: expansive ocean, rugged mountains, urban skyline (fig. 2), rocky outcrops, and secluded canyons. Shaped by geologic forces, the coastal and mountain scenery provides the setting for visitors and residents to enjoy outdoor recreation. This setting and the enjoyment it provides is a fundamental resource and value of the park (National Park Service 2015a).

Born from converging, rotating, and sliding crustal plates, the Santa Monica Mountains are home to rare and beautiful natural features. These mountains, which are approximately 74 km (46 mi) long and 13 km (8 mi) wide, are part of the Transverse Ranges that stretch from the Mojave Desert in southeastern and central California and adjoining states into the Pacific Ocean. The Channel Islands top the submerged portion of the Transverse Ranges. On land, the ranges include the Santa Monica, Santa Ynez, San Gabriel, and San Bernardino mountains. With respect to the National Park System, part of Joshua Tree National Park lies on the eastern end of the range, Santa Monica Mountains National Recreation Area is part of the range, and Channel Islands National Park marks the western extent of the range (Lillie 2005).

Figure 2. Photograph of Los Angeles skyline. The Santa Monica Mountains offer easy access to surprisingly wild places, while providing cityscape views from chaparral-covered hills. Photograph from Ray Sauvajot (Santa Monica Mountains National Recreation Area, supervisory ecologist, GRI scoping meeting presentation, 7 May 2008).

In contrast to most other mountain ranges in California, which run roughly north to south, the Transverse Ranges are oriented east–west. They were originally oriented north–south but rotated approximately 90° clockwise as a result of complex interactions at a plate boundary. The evolution of this plate boundary includes the subduction and breakup of the former Farallon plate, fragmentation of the rim of the continent, and the development of the San Andreas Fault system, which marks the present-day transform plate boundary.

The park protects one of the world's largest and most significant examples of a Mediterranean-type ecosystem. Fully functioning native habitats with high biodiversity associated with the Mediterranean ecosystem is another of the park's fundamental resources and values (National Park Service 2015a). A Mediterranean ecosystem is characterized by evergreen or drought deciduous shrublands such as "chaparral" in California. The old world Mediterranean maquis, the Chilean matorral, South African fynbos, and the Australian mallee scrub communities characterize the Mediterranean ecosystem elsewhere in only five relatively small areas around the planet. These areas are distributed between roughly 30° and 40° latitude, north and south, and are located along the western edges of continents (fig. 3). In these locales, the climate—which is characterized by mild, rainy winters and warm, dry summers—is moderated by cold ocean currents (National Park Service 2015c).

The world's Mediterranean climate has been highly favored by humans, and these regions, which cover only about 2% of Earth's total land area, have been densely populated and impacted. Urbanization along the southern California coastline has resulted in the loss of significant natural areas and increasing human impacts to natural systems. Nevertheless, the Mediterranean-type ecosystem of southern California has been identified as one of the world's "hot spots" for biodiversity (National Park Service 2015c).

Akin to its ecology and geology, the management of the park is very complex and fragmented (Ray Sauvajot, Santa Monica Mountains National Recreation Area, supervisory ecologist, scoping meeting communication, 7 May 2008). The park consists of a web of protected places. Twenty different landowner types, including the entire City of Malibu, and more than 70 stakeholder groups share responsibilities and jurisdiction within the park's authorized boundary. A total of 62,020 ha (153,250 ac) are divided among private landowners, local parks, California State Parks, and the National Park Service. The National Park Service is steward of 9,510 noncontiguous hectares (23,500 ac) (National Park Service 2015a).

When Congress established Santa Monica Mountains National Recreation Area on 10 November 1978, it became the 295th unit of the National Park System. In the National Parks and Recreation Act of 1978, which authorized the park, Congress noted "significant scenic, recreational, educational, scientific, natural, archeological, and public health benefits provide[d] by the Santa Monica Mountains and adjacent coastline area" (National Park Service 2015d). Completed in 2015, the park's foundation document contains significance statements about high biodiversity in a Mediterranean ecosystem; recreational opportunities in a national park gateway; scientific understanding of native vegetation communities, archeological sites, and geologic and paleontological features, all in proximity to numerous research institutions; scenic resources, extending from Point Mugu to downtown Los Angeles, including 64 km (40 mi) of coastline (Curdts 2011); and film-making history where landscapes continue to provide backdrops for film production today (see National Park Service 2015a). These statements express why the park's resources and values are important enough to merit designation as a unit of the National Park System.

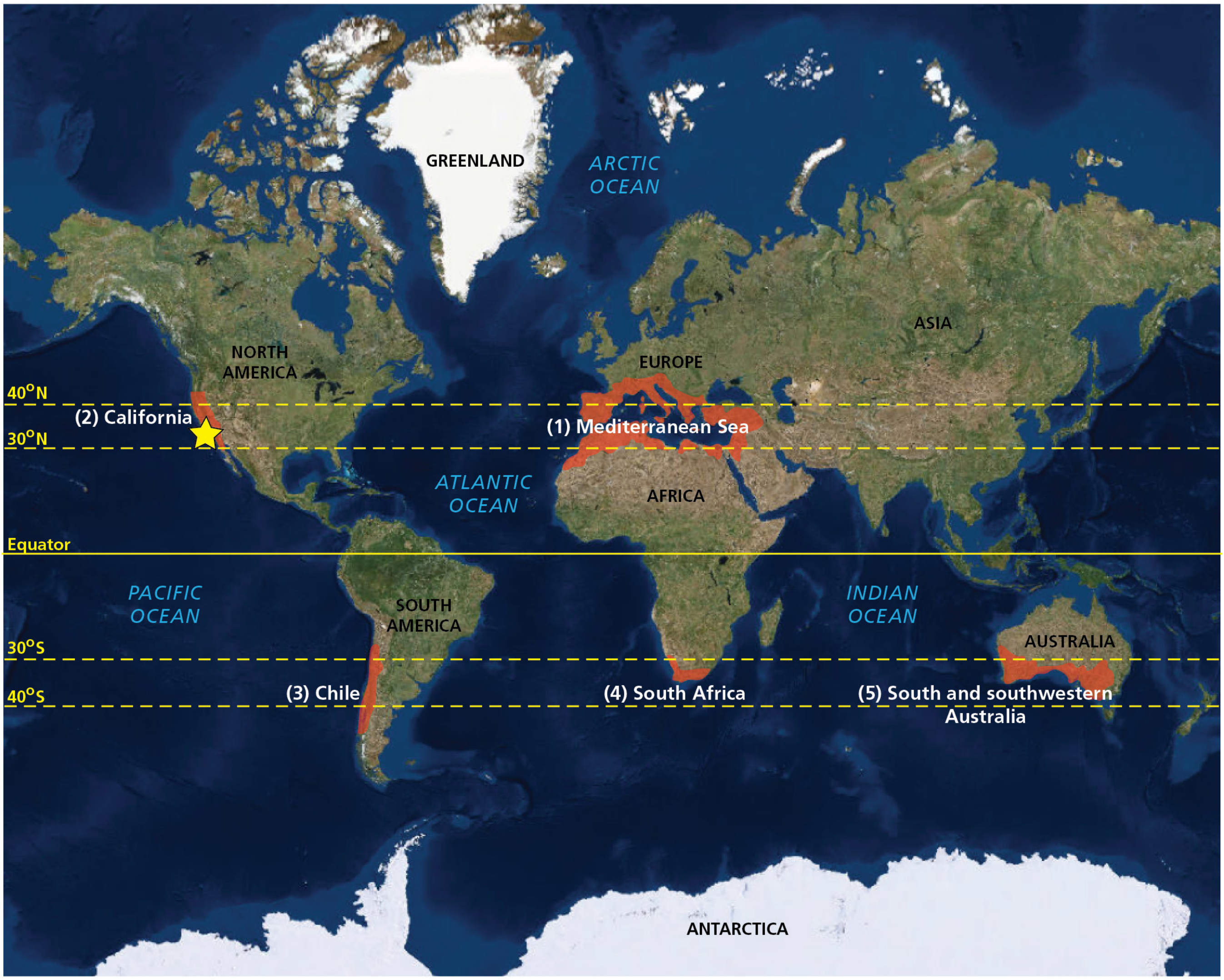

Figure 3. World map of Mediterranean ecosystems. The Mediterranean ecosystem occurs in five relatively small areas around the planet: (1) the area bordering the Mediterranean Sea, (2) southern California and northern Baja California (yellow star indicates the location of the park), (3) central Chile, (4) the Cape region of South Africa, and (5) southwestern and southern Australia. These areas are distributed between roughly 30° and 40° latitude—north and south—and are located along the western edges of continents where cold ocean currents moderate the climate.

Geologic Features and Processes

This section describes noteworthy geologic features and processes in Santa Monica Mountains National Recreation Area.

During the 2008 scoping meeting (see scoping summary by KellerLynn 2008) and 2015 conference call, participants (see Appendix A) identified the following geologic features and processes in the park. Landscape-scale features and processes are discussed before smaller scale features and processes.

- Plate Boundaries
- Faults
- Folds
- Unconformities
- Rock Types
- Formations
- Type Sections
- Paleontological Resources
- Landslides
- Fluvial Features
- Cave and Karst Resources
- Eolian Features and Processes
- Marine and Coastal Resources

These geologic features and processes contribute to the park's significance of scientific understanding, scenic resources, and film-making history (see "Geologic Setting and Significance"). Additionally, the park's geologic features and processes are fundamental resources and values, specifically as they relate to the park's coastal and mountain landscapes, which are shaped by ongoing geologic forces. Also, paleontological resources are an "other important resource and value" identified in the park's foundation document (National Park Service 2015a).

Plate Boundaries

Profound changes have taken place at the western edge of the North American continent, which is the site of an evolving plate boundary. The park's geologic story is wrapped up in this complex story of plate-boundary evolution (see table 1 and "Geologic History" section). The park contains geologic evidence of all three types of plate boundaries—convergent, divergent, and transform.

Convergent Boundary

Places where tectonic plates are moving toward each other are convergent boundaries. Convergence can occur between an oceanic and a continental plate, between two oceanic plates, or between two continental plates. In the case of southern California, convergence was between the oceanic Farallon plate and the continental North American plate. The Farallon plate subducted beneath the North American plate, and Earth's crust (outermost layer) was recycled into Earth's mantle (zone below the crust and above the core). Convergence created a subduction zone from the Mesozoic Era through the early to middle Cenozoic Era (Oligocene Epoch) (fig. 4).

The former convergent boundary in southern California is characterized by four belts or assemblages of rocks: (1) the Sierra Nevada magmatic arc, (2) the Western Foothills–Peninsular Ranges accreted arcs, (3) the Great Valley forearc basin, and (4) the Coast Ranges–Franciscan Group accretionary wedge (fig. 4). In southern California, elements of these belts can be recognized, but the assemblages of rocks have been reorganized by more recent (Neogene Period) faulting and folding (Atwater 1998). Subduction continues today off the coast of northern California, Oregon, Washington, and British Columbia as part of the Cascadia subduction zone.

Convergent Boundary: Magmatic Arc

The granitic rocks (**Kgr**) that intruded the oldest rocks in the park—the Santa Monica Slate ("**Jsm**" map units)—represent the "magmatic arc" belt, which is an arcuate line of plutons, volcanic rocks, or active volcanoes formed at a convergent boundary. Most of the magma forms by melting in the zone above the downgoing plate. The Sierra Nevada and Peninsular Ranges, north and south of the park respectively, are part of the magmatic arc belt. Yosemite National Park (see GRI report by Graham 2012a) offers exceptional views of the "roots" of uplifted magma chambers of the magmatic arc now exposed as granitic mountains in that part of the state. The bedrock at Cabrillo National Monument in San Diego contains fragments of the rising Peninsular Ranges, which were transported by

Table 1. Geologic summary of rock units in Santa Monica Mountains National Recreation Area

The rock units in the park are separated into table 1a and 1b with respect to the Malibu Coast Fault. The Monterey Shale, Trancas Formation, and Zuma Volcanics are only exposed south of the fault, though they are coeval with map units north of the fault. The rocks north of the fault are best correlated with the Transverse Ranges whereas the rocks south of the fault are best correlated with the northern Peninsular Ranges.

Many investigators—for example, Crouch and Suppe (1993), Nicholson et al. (1994), Atwater (1998), and Olson (2006)—have suggested the timing of events in the complex tectonic history of the Transverse Ranges. This table uses the approximate dates provided by Fritsche and Weigand (2008), which served as a handout during the 2008 GRI scoping meeting.

Colors in the first column (ages of map units) are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps. Shading in the Tectonic and Depositional Setting column highlights the major tectonic regimes: pink = subduction, blue = transition from subduction to transtension, tan = transtension, and violet = transpression (see "Geologic History" section). Yellow shading in Map Unit column indicates rock units with type sections in the park (see table 4). See tables 2 and 3 for explanations of rock types.

Table 1a. Rock units north of the Malibu Coast Fault.

Age of Map Unit from GRI GIS Data	Date Reported by Fritsche and Weigand (2008) in millions of years ago	Map Unit (symbol)	Rock or Sediment Type	Tectonic and Depositional Setting
Quaternary (late Holocene)	Not reported	Artificial fill (**Qaf**)	Compacted, engineered or noncompacted, nonengineered sand, silt, and gravel	Transpression. Developed areas, altered or constructed by humans.
Quaternary (late Holocene)	Not reported	Alluvium (**Qa**)	Unconsolidated gravel, sand, and silt	Transpression. Active or recently active streambeds.
Quaternary (Holocene)	Not reported	Wash deposits (**Qw** and **Qw1**)	Unconsolidated gravel, sand, and silt	Transpression. Active or recently active streambeds.
Quaternary (late Holocene)	Not reported	Beach deposits (**Qb**)	Loose sand	Transpression. Active beaches.
Quaternary (late Holocene)	Not reported	Eolian deposits (**Qe**)	Loose sand, silty sand, and silt	Transpression. Mostly transitory dunes against beach-facing cliffs.
Quaternary (late Holocene)	Not reported	Alluvial fan (**Qf**)	Unconsolidated boulders, cobbles, gravel, sand, and silt	Transpression. Active and recently active alluvial fans.
Quaternary (late Holocene)	Not reported	Active coastal estuarine deposits (**Qes**)	Submerged/saturated silty clay	Transpression. Estuaries.
Quaternary (Holocene and Pleistocene?)	Not reported	Landslide deposits (**Qls**)	Rock detritus from bedrock and surficial materials, broken in varying degrees	Transpression. Slopes.
Quaternary Period (Holocene and Pleistocene epoch)	Not reported	Young alluvium (**Qya**, **Qya2**, and **Qya1**)	Unconsolidated silt, sand, and gravel	Transpression. Subaerial canyon floors.
Quaternary (Holocene and late Pleistocene)	Not reported	Young alluvial-fan deposits (**Qyf** and **Qyf2**)	Unconsolidated gravel, sand, and silt; boulders near mountain fronts	Transpression. Flooding streams and debris flows.
Quaternary (middle to late Pleistocene)	Not reported	Old alluvium (**Qoa**)	Unconsolidated to moderately indurated gravel, sand, and silt	Transpression. Valley floor, floodplain, or alluvial fans.
Quaternary (middle Pleistocene)	Not reported	Old fan deposits (**Qof1**, **Qof2**, and **Qof4**)	Slightly to moderately consolidated silt, sand, and gravel	Transpression. Alluvial fans.
Quaternary (late Pleistocene)	Not reported	Old shallow marine deposits on wave-cut surface (**Qom**)	Generally unconsolidated sand, silty sand, and gravel. Some deposits have calcite cement.	Transpression. Coastline at former sea level.

Table 1a. Rock units north of the Malibu Coast Fault, continued.

Age of Map Unit from GRI GIS Data	Date Reported by Fritsche and Weigand (2008) in millions of years ago	Map Unit (symbol)	Rock or Sediment Type	Tectonic and Depositional Setting
Quaternary–Tertiary (late Pliocene to early Pleistocene epochs)	Not reported	Sedimentary rocks of the Pacific Palisades area (**QTms**)	Sedimentary (siltstone and sandstone)	Transpression. Marine basin with possible slumping along margins.
n/a	~4	Tectonic regime changes from transtension to transpression. Gulf of California opens. Modern San Andreas Fault forms. Begin uplift of Santa Monica Mountains.		
Tertiary (late and middle Miocene)	~12–4	Modelo Formation (**Tm**, **Tmd**, **Tms**, **Tmb**)	Sedimentary (sandstone and shale)	Transtension. Submarine fan.
n/a	**~13–12**	**7th unconformity in the park's rock record—angular unconformity**		
Tertiary (Miocene)	~17–13	Calabasas Formation (**Tcb**, **Tcbs**, **Tcbmp**, **Tcbn**, **Tcbd**, **Tcbl**, and **Tcbe**) *Type section (see table 4).*	Sedimentary (sandstone and shale; breccia)	Transtension. Offshore marine, with deposition by turbidity currents.
Tertiary (middle Miocene)	~17–15	Conejo Volcanics (**Tco**, **Tcod**, **Tcoaf**, **Tcoaa**, **Tcoab**, **Tcob**, **Tcoadb**, **Tcobf**, **Tcobb**, **Tcop**, **Tcobz**, **Tcom**, **Tcos**, and **Tcor**) *Type section (see table 4).*	Igneous, volcanic (basalt, andesitic basalt, basaltic andesite, andesite, and dacite)	Transtension. Submarine eruptions that built into shield volcanoes that rose above sea level and produced subaerial eruptions.
Tertiary (middle Miocene)	Not reported	Intrusive rocks (**Ti**, **Tid**, **Tia**, and **Tib**)	Igneous, intrusive (diabase, andesite, and basalt)	Transtension. Marine (intruded into Topanga Canyon Formation). Exposed in central and western Santa Monica Mountains.
Tertiary (middle Miocene)	Not reported	Mixed rocks (**Tim**)	Igneous, intrusive (basalt), intruded into siltstone and sandstone	Transtension. Marine (intruded into Topanga Canyon Formation). Exposed in central and western Santa Monica Mountains.
Tertiary (middle and early Miocene)	Not reported	Topanga Group, intrusive and extrusive volcanic rocks (**Ttb**)	Igneous, basalt flows and related hypabyssal (shallow intrusive) basaltic rocks	Transtension. Intruded into undivided Topanga Group rocks (**Tt**). Have an affinity with Topanga Group rocks in the Los Angeles Basin. Exposed in eastern Santa Monica Mountains.
n/a	~18	Begin rotation of the Western Transverse Ranges block. Extension. Volcanism.		
n/a	**~18–17**	**6th unconformity in the park's rock record—angular unconformity**		
n/a	~20	Tectonic regime changes from subduction to transtension. Capture of the Monterey microplate by the Pacific plate.		
Tertiary (middle and early Miocene)	~21–18	Topanga Canyon Formation (**Ttc**, **Ttcc**, **Ttcf**, **Ttcs**, **Ttcb**, **Ttcbs**, and **Ttce**) *Type section (see table 4).*	Sedimentary (sandstone, siltstone, mudstone, and conglomerate)	Transition from subduction to transtension. Marine, nearshore marine, and nonmarine (river).
Tertiary (early Miocene and Oligocene)	~28–21	Vaqueros Formation (**Tv**, **Tvn**, and **Tvd**)	Sedimentary (sandstone, siltstone, and mudstone)	Transition from subduction to transtension. Marine and nearshore marine.
Tertiary (early Miocene)	~28–21	Sespe Formation, Piuma Member (**Tsp**)	Sedimentary (sandstone and siltstone)	Transition from subduction to transtension. Nonmarine (lake and lagoon).
n/a	~28	East Pacific Rise (spreading center) makes contact with western margin of the North American plate.		

Table 1a. Rock units north of the Malibu Coast Fault, continued.

Age of Map Unit from GRI GIS Data	Date Reported by Fritsche and Weigand (2008) in millions of years ago	Map Unit (symbol)	Rock or Sediment Type	Tectonic and Depositional Setting
Tertiary (early Miocene, Oligocene, and late Eocene)	29–28	Sespe Formation (**Ts**)	Sedimentary ("red beds"—sandstone, mudstone, and conglomerate)	Subduction. Deposition of forearc sediments. Nonmarine (river channel, floodplain, and delta).
n/a	**~36–29**	**5th unconformity in the park's rock record—disconformity. Approach of the East Pacific Rise spreading center.**		
Tertiary (early Miocene, Oligocene, and late Eocene)	~41–36	Sespe Formation (**Ts**)	Sedimentary ("red beds"—sandstone, mudstone, and conglomerate)	Subduction. Deposition of forearc sediments. Nonmarine (river channel, floodplain, and delta).
n/a	**~48–41**	**4th unconformity in the park's rock record—angular unconformity**		
Tertiary (early to middle Eocene)	~50–48	Llajas Formation (**Tl**)	Sedimentary (sandstone, siltstone, and conglomerate)	Subduction. Deposition of forearc sediments. Shallow marine and coastal alluvial fan.
n/a	**~55–50**	**3rd unconformity in the park's rock record—angular unconformity**		
Tertiary (late Paleocene to early Eocene)	~58–55	Santa Susana Formation (**Tss** and **Tssl**)	Sedimentary (shale [some with limestone concretions], mudstone, and siltstone with interbeds of sandstone and lenses of pebble-cobble conglomerate; scattered lenses and pods of algal limestone in siltstone sequences)	Subduction. Deposition of forearc sediments. Marine and nearshore marine.
Tertiary (early? Paleocene Epoch)	~58–55	Las Virgenes Sandstone (**Tlv**)	Sedimentary (sandstone and mudstone)	Subduction. Deposition of forearc sediments. Nearshore marine and nonmarine (coastal river).
Tertiary (Paleocene)	~58–55	Simi Conglomerate (**Tsi**)	Sedimentary (cobble-boulder conglomerate)	Subduction. Deposition of forearc sediments. Nonmarine (alluvial fans and braided rivers).
n/a	**~75–58**	**2nd unconformity in the park's rock record—angular unconformity. Runyon Canyon erosion surface (associated with "K-T" boundary).**		
Late Cretaceous	Not reported	Chatsworth Formation (**Kc**)	Sedimentary (turbidite sandstone)	Subduction. Deposition of forearc sediments. Marine (mostly deposited by turbidity currents).
Late Cretaceous	~90–75	Tuna Canyon Formation (**Kt**, **Kte**, **Ktd**, **Ktc**, and **Ktb**) *Type section (see table 4).*	Sedimentary (sandstone, siltstone, and conglomerate)	Subduction. Deposition of forearc sediments. Marine.
Late Cretaceous	~91–90	Trabuco Formation (**Ktr**)	Sedimentary (conglomerate)	Subduction. Deposition of forearc sediments. Nonmarine (alluvial fans in "Tarzana Canyon").
n/a	**~102–91**	**1st unconformity in the park's rock record—nonconformity. Erosion of subaerial "Tarzana Canyon."**		
Late Cretaceous	~102	Granitic rocks (**Kgr**)	Igneous, intrusive	Subduction. Intrusion associated with magmatic arcs. Igneous intrusion into the Santa Monica Slate.
Late Jurassic	~156–152	Santa Monica Slate (**Jsm**, **Jsms**, and **Jsmp**) *Type section (see table 4).*	Metamorphic	Subduction. Accretion of island arcs. Deposited in a marine setting and later metamorphosed.

Table 1b. Rock units south of the Malibu Coast Fault.

Age of Map Unit from GRI GIS Data	Date Reported by Fritsche and Weigand (2008) in millions of years ago	Map Unit (symbol)	Rock or Sediment Type	Tectonic and Depositional Setting
Tertiary (Miocene)	Not reported	Monterey Shale (**Tmt** and **Tmtd**)	Sedimentary (shale, siltstone, sandstone)	Transtension. Deep, isolated, distal marine basins.
Tertiary (middle and early Miocene)	Not reported	Trancas Formation (**Tr** and **Tra**) *Type section (see table 4).*	Sedimentary (mudstone, shale, claystone, and sandstone; also San Onofre Breccia)	Transtension. Marine
Tertiary (middle and early Miocene)	Not reported	Zuma Volcanics (**Tz**) *Type section (see table 4).*	Igneous, volcanic (basalt, andesite, and dacite)	Transtension. Erupted into extensional marine basin.
n/a	~18	Begin rotation of Western Transverse Ranges block. Extension. Volcanism.		
n/a	~20	Tectonic regime changes from subduction to transtension. Microplate capture.		

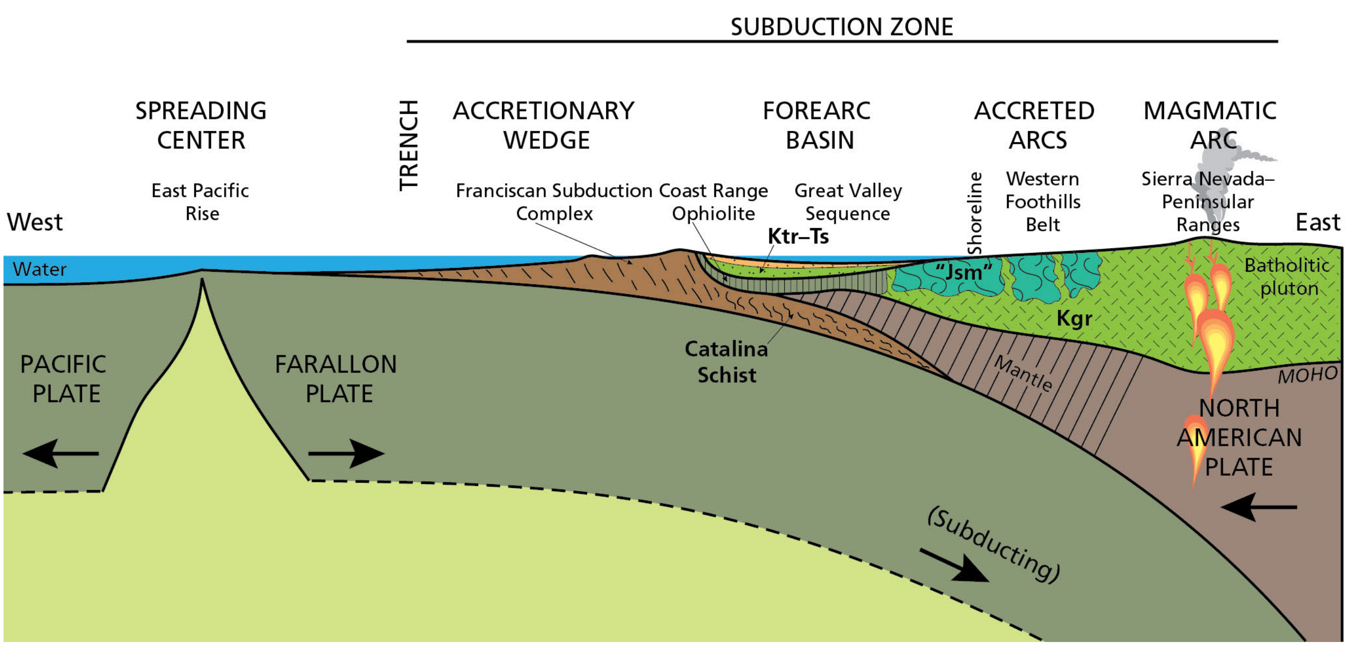

Figure 4. Graphic of subduction zone. The park contains rocks and structures formed during subduction of the Farallon plate. The Santa Monica Slate ("Jsm" map units) is part of the "accreted arcs" belt. Granitic rocks (Kgr) are part of the "magmatic arc" belt. The sequence of sedimentary rocks consisting of the Trabuco (Ktr) through the Sespe (Ts) formations (see table 1) represents deposition in the "forearc basin" belt. Metamorphosed, mid-crustal rocks such as the Cretaceous Catalina Schist (not exposed in the park) represent the "accretionary wedge" of material under the "forearc basin" sediments. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Crouch and Suppe (1993, figure 2) and Lillie (2005, figure 7.6).

streams and deposited in a huge submarine fan (see GRI report by KellerLynn in preparation).

Convergent Boundary: Accreted Arcs

The Santa Monica Slate ("**Jsm**" map units) represents the "accreted arcs" belt. These rocks accumulated between 156 million and 152 million years ago in a basin within an island arc system (generally curved linear belt of volcanoes above a subduction zone), which collided with the continental margin and later accreted to the edge of the North American continent.

Convergent Boundary: Forearc Basin

Nine of the park's sedimentary rock formations—Trabuco (**Ktr**) through Sespe (**Ts**) formations (see table 1)—represent the "forearc basin" belt. The forearc basin is a sedimentary basin that lies between the arc and the shelf break at a convergent plate boundary.

Transgressive–Regressive Cycles

The rocks of the Great Valley forearc basin record multiple cycles of marine transgression and regression. A transgression occurs when the land surface subsides

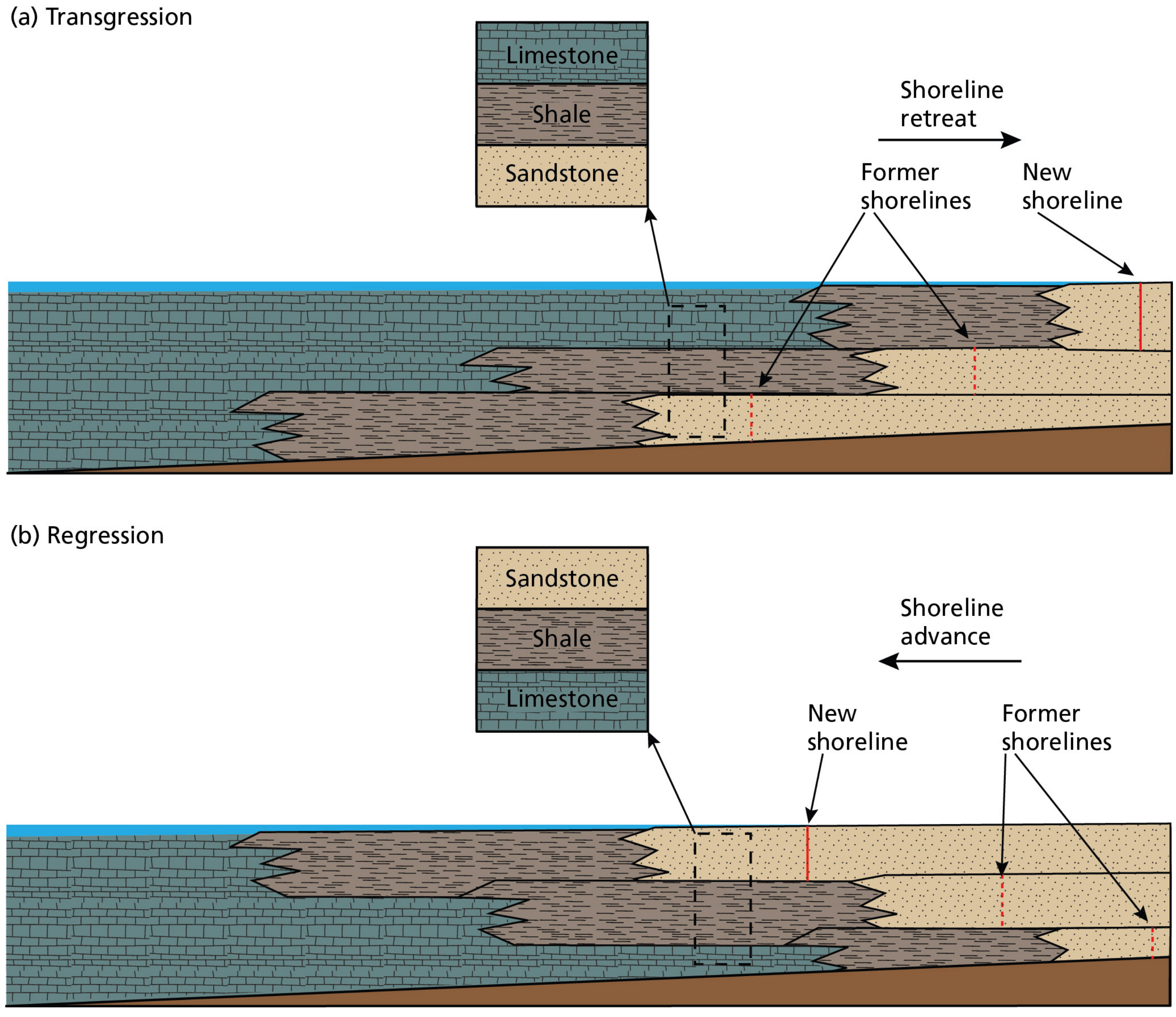

Figure 5. Graphic of a transgression and a regression. (a) During a transgression, the sea advances over the edge of the continent, causing the shoreline to retreat. As the water deepens, more landward type sediments are covered by more marine type sediments. (b) During a regression, the sea retreats and the shoreline advances. Deep-water sediments are covered by more landward type sediments. An example of a marine transgression in the park's rock record includes the Simi Conglomerate (Tsi), Las Virgenes Sandstone (Tlv), and Santa Susana Formation (Tss and Tssl). Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Lillie (2005, figure 4.23).

or sea level rises, causing the ocean to advance over the continental edge (a landward migration of the shoreline). A transgression results in an "onlap sequence" where layers of nonmarine sediments are covered by shallow-marine sediments, and then by deeper marine sediments as the water depth gradually increases. Thus, a transgressive sequence will show, for example, nonmarine sandstone overlain by shallow-marine shale that is in turn overlain by offshore and shelf marine limestone. By contrast, as the land surface rises or the sea gradually moves offshore during a marine regression (an "offlap sequence"), the rock sequence is reversed, with marine sediments gradually covered by more terrestrial materials (fig. 5). Multiple transgressive-regressive events or cycles result in the intertonguing of marine and terrestrial sediments. Intertonguing is the intergradation of different rock layers commonly shown in a vertical succession of wedge-shaped stratum (see fig. 40).

An example of a marine transgression in the park's rock record includes the Simi Conglomerate (**Tsi**), Las Virgenes Sandstone (**Tlv**), and Santa Susana Formation (**Tss** and **Tssl**). In the Santa Monica Mountains, the Simi Conglomerate consists of conglomerate and minor interbedded sandstone representing braided river deposits on an alluvial plain. This unit also includes iron-stained red beds and concentrations of carbonaceous material that serve as a regional marker for relative dating in the rock record. The Las Virgenes Sandstone consists of a lower unit of sandstone deposited by meandering streams on a coastal plain. In some locations, this unit also contains red beds and a very distinctive bed of iron pisoliths (small, ovoid accretionary particles). The upper part of the Las Virgenes Sandstone consists of sandstone deposited in a nearshore marine environment. Sandstone in the upper unit intertongues with the Santa Susana Formation, which consists of nearshore to offshore and shelf deposits of interbedded mudstone and sandstone with lenses of storm-lag deposits (coarse-grained material that is left behind following a storm) consisting of mollusk shells and, in some places, a calcareous algae marker bed.

Convergent Boundary: Accretionary Wedge

As material is scraped off a subducting plate then becomes accreted (attached) to the overriding plate, an "accretionary wedge" forms. Portions of the accretionary wedge rise above sea level as sediment and rock are compressed, folded, and faulted. Elsewhere in California, the Coast Ranges represent an accretionary wedge of uplifted oceanic rocks. The Coast Ranges–Franciscan Group accretionary wedge forms the landscape of Golden Gate National Recreation Area (see GRI report by Port 2016). In the Santa Monica Mountains, the Cretaceous Catalina Schist represents the accretionary wedge. Catalina Schist is not exposed in the park but was encountered at depth in a well located south of the Malibu Coast Fault (Yerkes and Campbell 1979). Fragments of Catalina Schist comprise the San Onofre Breccia (consisting of angular clasts; table 2). The breccia is a distinctive part of the Trancas Formation (**Tr** and **Tra**), which is exposed in the park south of the Malibu Coast Fault.

Divergent Boundary

Divergent boundaries occur along spreading centers where plates are moving apart and new crust is created by magma pushing up from the mantle. The East Pacific Rise is the divergent boundary/spreading center associated with the park's geologic story (fig. 6). As the East Pacific Rise approached the margin of North America (see "Geologic History" section), subduction of young, buoyant crust associated with the spreading center contributed to the uplifts recorded by the terrestrial Sespe Formation (Atwater 1998; see "Sedimentary Rocks" section). Also, the unconformity in the middle of the lower Sespe Formation (**Ts**) between 36 million and 29 million years ago is evidence of the approach of the East Pacific Rise (Fritsche and Weigand 2008; see "Unconformities" section).

Transform Boundary

Transform boundaries form where Earth's crust is neither produced nor destroyed as crustal plates slide horizontally past each other. Following subduction, the plate boundary in southern California became characterized by transform plate motion. Initially, the new transform plate boundary (between the Pacific plate and North American plate) had significant amounts of extension and associated normal faulting (see "Faults" section) along which basins dropped down, similar to the Basin and Range province (Bartolomeo and Longinotti 2010). This stage in the development of the plate boundary is referred to as "transtension" (transform plate motion and extension). Transtension is responsible for the rotation of the Western Transverse Ranges block (see "Transverse Ranges" section below). "Transpression" (transform

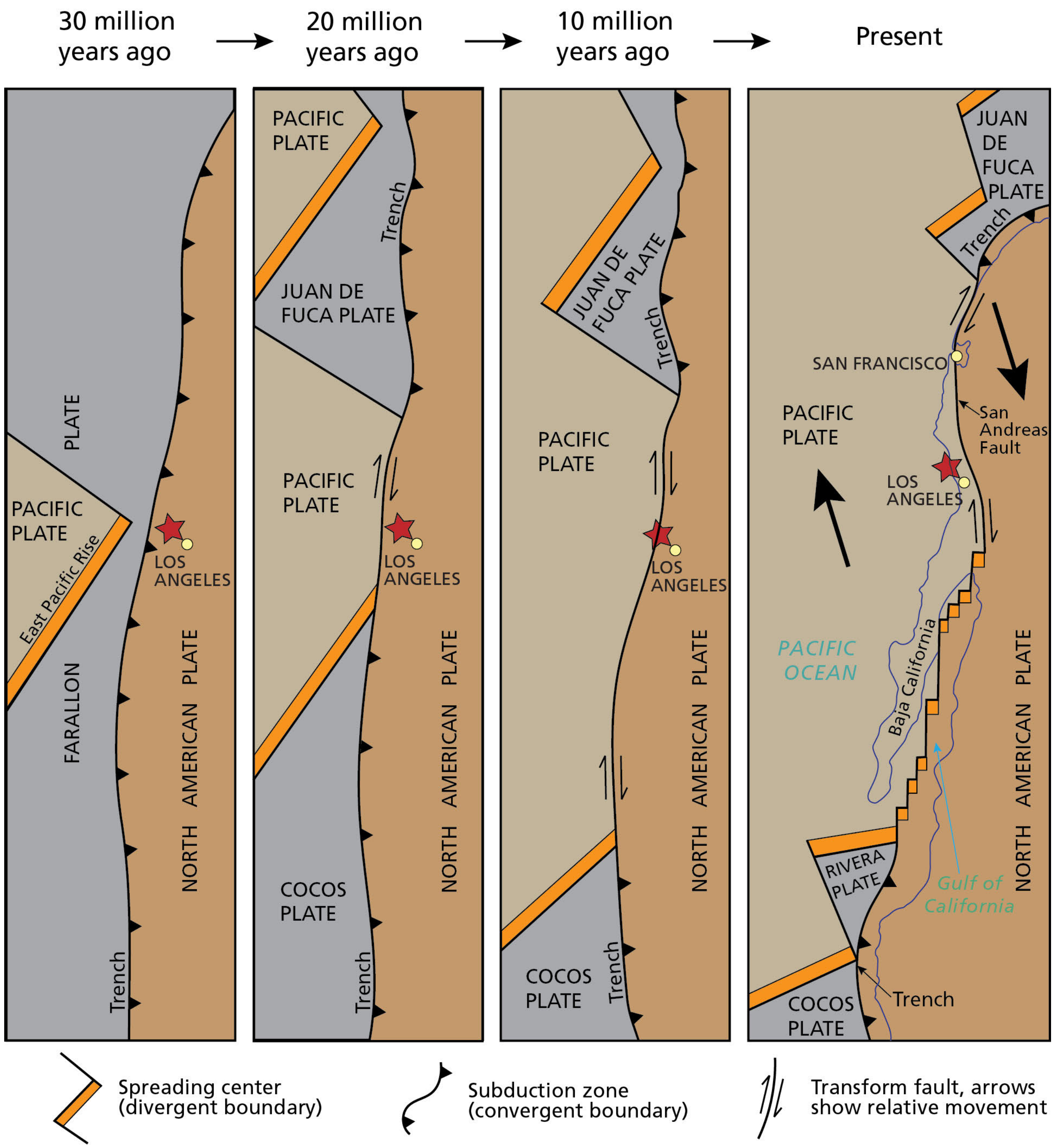

Figure 6. Graphic of the North American plate boundary over time. The four panels illustrate the subduction of the Farallon plate, as it was progressively consumed beneath the North American plate, leaving only the Juan de Fuca, Rivera, and Cocos plates as remnants today. As the East Pacific Rise made contact with the North American plate, the Farallon plate east of the rise began to fracture into microplates. As contact between the Pacific and North American plates lengthened, transtension (transform plate motion and extension) replaced subduction about 20 million years ago. Rotation of the Western Transverse Ranges block (see fig. 7) began about 18 million years ago; rotation is ongoing locally. About 4 million years ago, the tectonic regime changed from transtension to transpression (transform plate motion and compression). Large, black arrows show the sense of relative motion between the Pacific and North American plates. The red star indicates the location of the park. Note its progression from the North American plate to the Pacific plate as the plate boundary evolved. The San Andreas Fault represents the present plate boundary. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Kious and Tilling (1996, p. 7).

plate motion and compression) followed transtension and characterizes the present-day boundary. Transpression is responsible for the development of the San Andreas Fault system (see “San Andreas Fault” section below).

Transform Boundary: Transverse Ranges

Rather than being oriented north–south or northwest–southeast as most of the mountains in California, or North America for that matter, the Transverse Ranges and their associated folds and faults (see “Faults” and “Folds” sections) are oriented east–west. The ranges’ orientation illustrates how blocks of Earth’s crust can rotate, like ball bearings, when caught in a zone of deformation at a plate boundary.

The Western Transverse Ranges block was originally part of a fault-bounded crustal block within the North American plate. During the transtensional phase of the plate boundary (see “Geologic History” section), it was one of three crustal blocks that rifted away from the continental margin, became attached to the Pacific plate, and began to migrate to the northwest, assuming relative Pacific plate motion (Atwater 1998). The Western Transverse Ranges block was the most inland of these blocks and, therefore, the most deeply embedded into the crust. As the Western Transverse Ranges block began to move with the Pacific plate, its northern end, which was essentially locked into the North American crust, did not break away. As a result, the central and southern portions of the Western Transverse Ranges block began to rotate as a coherent structural unit with the locked northern end acting as a hinge (Olson 2006). Before rotation, the Western Transverse Ranges block was oriented north–south, approximately adjacent to the northern Peninsular Ranges at present-day San Diego and Anaheim. To reach the present configuration of the Transverse Ranges, the block rotated clockwise approximately 90°–110° at an average rate of 5° to 6° per million years (fig. 7; Hornafius et al. 1986; Luyendyk 1991). Tanya Atwater (University of California, Santa Barbara) developed an animation that shows the rotation of the Western Transverse Ranges block (see http://emvc.geol.ucsb.edu/2_infopgs/IP4WNACal/cCalifornia.html). This animation may help park staff and visitors alike to visualize the complex rotation scenario of the Western Transverse Ranges block.

Transform Boundary: San Andreas Fault

The San Andreas Fault extends roughly 1,300 km (810 mi) through California. The fault segment closest to the park is about 80 km (50 mi) to the northeast (fig. 8). The San Andreas Fault was first identified in 1895 by Professor Andrew Lawson at the University of California, Berkeley, who discovered the northern segment. It was named after San Andreas Lake, a small body of water that formed in a valley between

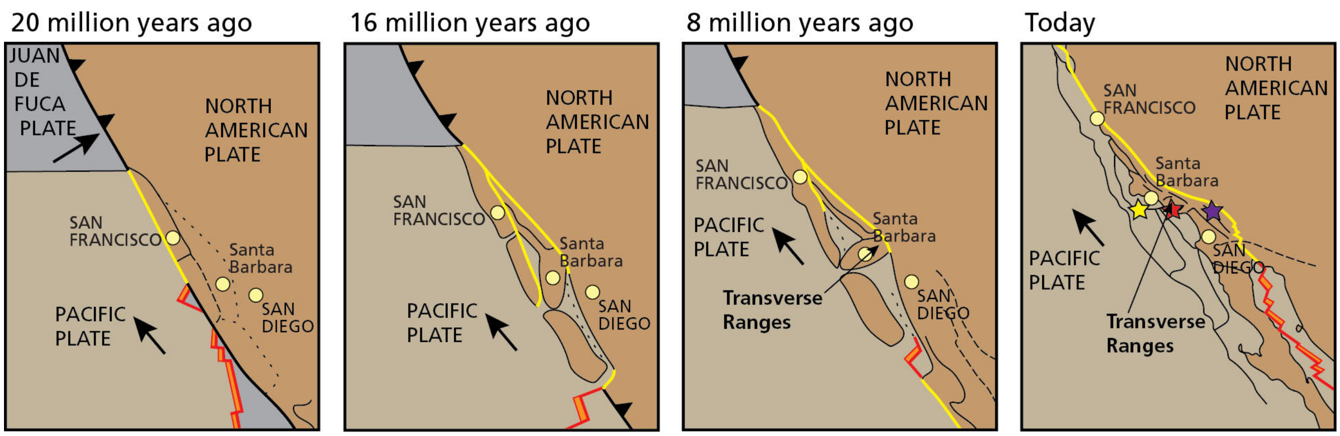

Figure 7. Graphic showing rotation of the Western Transverse Ranges block. As shown on the graphic, the crustal block associated with the city of Santa Barbara rolled like a ball bearing trapped within a zone of deformation at the plate boundary. Clockwise rotation of the block explains why the Transverse Ranges run east–west, unlike the northwest–southeast orientation of most mountain ranges in California. The Santa Monica Mountains, including the park (red star), lie within the Transverse Ranges. Channel Islands National Park (yellow star) marks the western extension of the ranges into the Pacific Ocean. Joshua Tree National Park (purple star) lies at the eastern end of the range. Note in the last panel how the San Andreas Fault makes a significant east–west bend at the Transverse Ranges; this is known as the “Big Bend.” Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Lillie (2005, figure 7.16).

Figure 8. Aerial image of the San Andreas Fault. The San Andreas Fault runs 1,300 km (810 mi) through California. It displays right-lateral strike-slip motion (see fig. 9). On the right-hand side of the fault, the North American plate is moving southeastward; on the left-hand side, the Pacific plate is moving northwestward. The park lies on the Pacific plate. This image is from NASA's Shuttle Radar Topography Mission (SRTM) with a graphic overlay that shows faults (white lines) that have been active in the late Quaternary Period. The fault data are from the US Geological Survey. Topographic shading derived from the SRTM elevation model was added to the Landsat image, with a false sun illumination from the left (southwest). This synthetic shading enhances the appearance of the topography. The Landsat image was acquired on 4 May 2001. The scale varies in this perspective: width of view is 134 km (83 mi); height/distance is 150 km (93 mi); vertical exaggeration is 1.8x. NASA Earth Observatory, Image of the Day: Los Angeles Faults, 24 December 2002. http://earthobservatory.nasa.gov/IOTD/view.php?id=3067. Annotations by Jason Kenworthy (National Park Service).

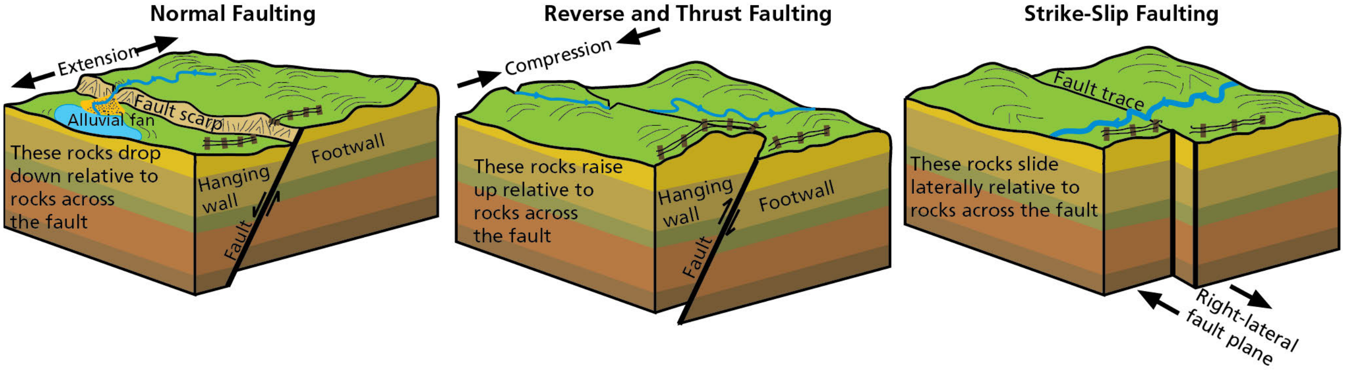

Figure 9. Graphic of fault types. Movement occurs along a fault plane. Footwalls are below the fault plane, and hanging walls are above. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging wall up relative to the footwall. A thrust fault is a type of reverse fault that has a dip angle of less than 45°. In a strike-slip fault, movement is horizontal. When movement across a strike-slip 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. A strike-slip fault between two tectonic plates is called a transform fault. Transtension (transform plate motion and extension) is characterized by strike-slip and normal faulting. Transpression (transform plate motion and compression) is characterized by strike-slip faulting and reverse and thrust faulting. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

the Pacific and North American plates. Following the 1906 San Francisco earthquake, Lawson concluded that the fault extended all the way into southern California (Lawson 1908). In 1953, Mason L. Hill and Thomas Dibblee astounded the scientific community with their conclusion that hundreds of miles of lateral movement had occurred along the fault (Hill and Dibblee 1953). This idea, which was considered radical at the time, has since been substantiated by modern studies of plate-tectonic processes. GRI reports about Golden Gate National Recreation Area (Port 2016) and Pinnacles National Park (Port in preparation) provide descriptions of features associated with more "pure" transform (horizontal) plate motion in northern California, where extension and compression have played less of a role along the fault system than in the Transverse Ranges.

In recent times, the San Andreas Fault has taken up the bulk of the motion at the plate boundary and thus has come to be identified as the transform-plate boundary in popular scientific thought. In reality, however, many faults (see "Faults" section) make up a broad zone of deformation that composes today's plate boundary.

Faults

A fault is a fracture in rock along which movement has taken place. Movement along faults causes earthquakes (see "Earthquakes" section). The three primary types of faults are normal, reverse, and strike-slip (fig. 9). Faults are classified based on the motion of rocks on either side of the fault plane. The faults in the park are primarily reverse faults, in which the hanging wall (rock immediately above the fault plane) has been raised relative to the footwall (rock immediately below the fault plane). Reverse faults include thrust and

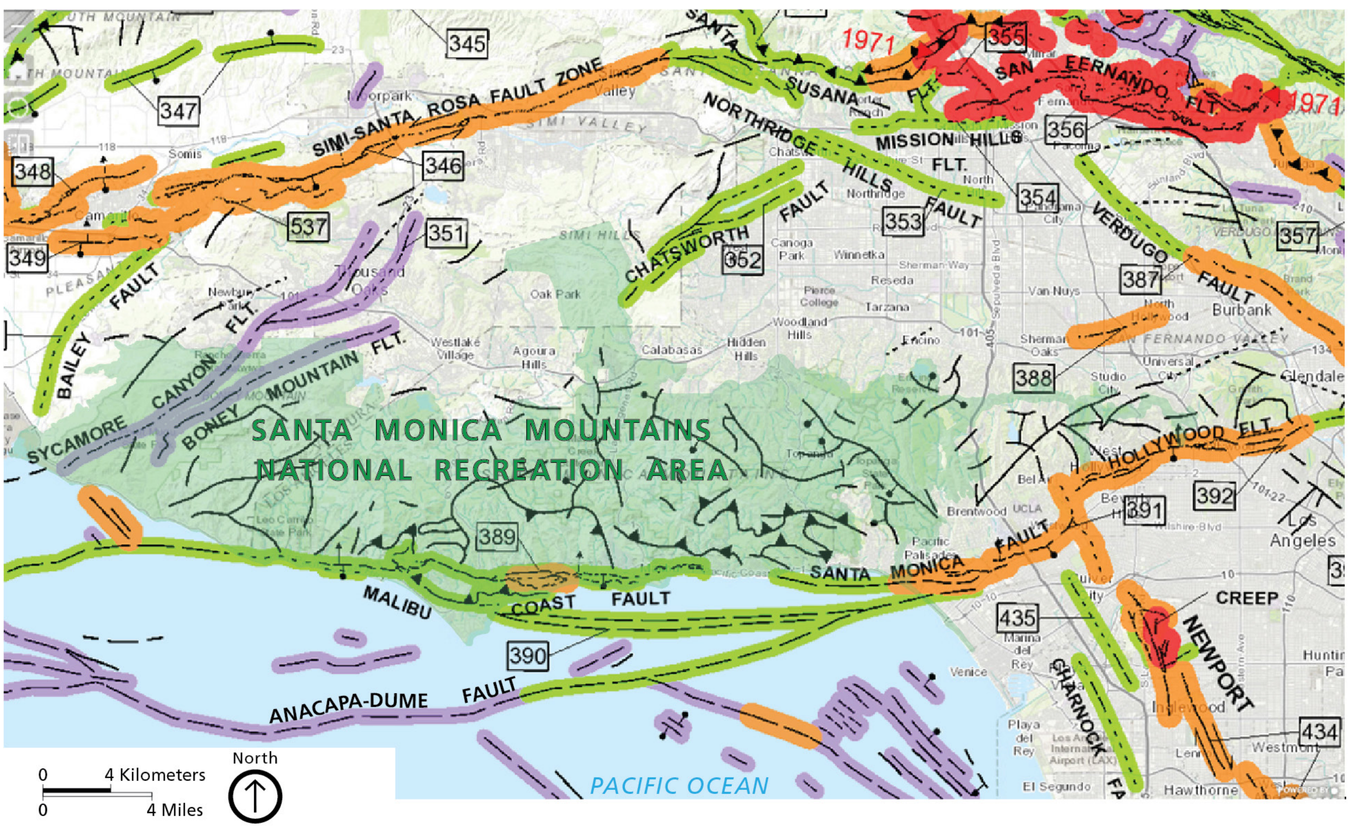

Figure 10. Screen capture of fault activity map of California. The Malibu Coast Fault and the Anacapa-Dume Fault are the two primary active faults in the park area. Faults are marked by solid and dashed black lines on the graphic. Low angle (thrust) faults are marked by lines with triangles that point in the direction of faulting. Bar and ball symbols indicate the downthrown side of a fault. Red indicates recent movement. Orange indicates movement 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). Numbers in boxes on the graphic are references to Jennings and Bryant (2010). California Geological Survey data at http://maps.conservation.ca.gov/cgs/fam/.

detachment faults. Thrust faults are reverse faults with a low angle (<45°) fault plane. Detachment faults are very low angle (nearly horizontal) reverse faults with large displacement (kilometers to tens of kilometers).

The Transverse Ranges are known for "blind thrust faults," which are typically low angle structures in areas of active folding (Jennings and Bryant 2010; see "Folds" section). The upper extent of the fault plane may terminate several kilometers below the ground surface (hence the term "blind" to describe these faults), and the surface expression is often delineated by young anticlines. These faults have produced strong earthquakes in California, such as the 1994 magnitude 6.7 Northridge earthquake (see "Earthquakes" section).

As recorded in the GRI GIS data, an estimated 1,040,089 m (3,412,365 ft or 646 mi) of fault segments cut through the park (see poster, in pocket). The primary active faults in the Santa Monica Mountains area are the Malibu Coast and the Anacapa-Dume faults (fig. 10; Pam Irvine, California Geological Survey, senior engineering geologist, telephone communication, 9 June 2016). The Malibu Coast Fault, which was mapped in the park and is included in the GRI GIS data, occurs both onshore and offshore. The Anacapa-Dume Fault occurs offshore and is not included in the GRI GIS data. Earthquake potential, hazards, and risk associated with the Malibu Coast, Anacapa-Dume, and other faults in the Santa Monica Mountains are discussed in the "Earthquakes" section.

Folds

Folds are curves or bends in originally flat structures, such as rock strata, bedding planes, or foliation. Visually, folds are some of the most spectacular structures on Earth. They are extraordinary displays of strain and conspicuous natural images of how the original shape of rock bodies can be changed during deformation (Davis 1984). Folds exist at multiple scales from a few meters at an outcrop (fig. 11) to regional folds that encompass many kilometers (see poster, in pocket).

The two primary types of folds are anticlines, which are convex ("A-shaped"), and synclines, which are concave ("U-shaped"). As bedrock is compressed by tectonic activity, anticlines and synclines form adjacent to one another. As mapped on the Los Angeles 30' × 60' quadrangle (Campbell et al. 2014; scale 1:100,000), the GRI GIS data include 164 fold segments—104 anticlines, one of which was deformed to an extent to become overturned, and 60 synclines (see poster, in pocket).

Figure 11. Photograph of folds. About 4 million years ago, the Santa Monica Mountains formed as a result of compression along the plate boundary. Complexly deformed shale beds of the Modelo Formation ("Tm" map units), shown here along Mulholland Highway about 2 km (1 mi) west of Las Virgenes Road, are evidence of compression. Note person at lower right corner for scale. Photograph from Eugene Fritsche (California State University, Northridge, Department of Geological Sciences, professor emeritus, GRI scoping presentation, 7 May 2008).

Approximately 102 million–91 million years ago (Cretaceous Period; fig. 13), compression, probably related to the ongoing subduction of the Farallon plate (see "Geologic History" section), produced folds in the Santa Monica Slate and created a generally north–south-trending anticline, which was later rotated (see "Transverse Ranges" section). Three angular unconformities in the park's rock record at 75 million–58 million, 55 million–50 million, and 48 million–41 million years ago are evidence of uplift and deformation along this anticline (see "Unconformities" and "Geologic History" sections).

Since about 4 million years ago, many secondary anticlines and synclines formed on the preexisting anticline (see poster, in pocket; Eugene Fritsche, California State University, Northridge, Department of Geological Sciences, professor emeritus, GRI scoping presentation, 7 May 2008). Campbell et al. (2014) mentioned the "Topanga Anticline" by name in their description of the Conejo Volcanics (**Tco**). Sedimentary rocks such as the Topanga Canyon Formation are uplifted in the Topanga Anticline in the park. A segment of the popular Backbone Trail climbs along the anticline (fig. 12).

Figure 12. Photograph of the Topanga Anticline. Rocks formations such as the Topanga Canyon Formation were raised up as part of the Topanga Anticline. Note the Backbone Trail traversing the flank of the anticline (arrow). Photograph by Alexandra Meyers, available via Wikimedia Commons https://commons.wikimedia.org/wiki/File:Topanga_Canyon.JPG (Creative Commons Attribution-Share Alike 4.0 International [CC BY-SA 4.0]; https://creativecommons.org/licenses/by-sa/4.0/deed.en).

These relatively young, northwest–southeast-trending folds in the park are related to a major change in the tectonic regime—from transtension (transform plate motion and extension) to transpression (transform plate motion and compression) (see "Geologic History" section). This change in plate motion caused extensive folding and the inversion of normal faults (indicative of extension) to reverse faults (indicative of compression). The Santa Monica Mountains are an outcome of compression and associated folding.

Unconformities

The rock record exposed in the park represents approximately 156 million years of geologic time, from the Jurassic Period to the present day (fig. 13). 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 park records seven unconformities (see table 1 and "Geologic History" section). In each case, uplift and erosion was followed by subsidence and renewed sedimentation. Five of the unconformities are angular unconformities, where lower rock layers are tilted at a different angle than overlying layers. One is a disconformity, which separates rock layers that are parallel. One is a nonconformity where sedimentary layers were deposited on top of igneous or metamorphic rocks (fig. 14).

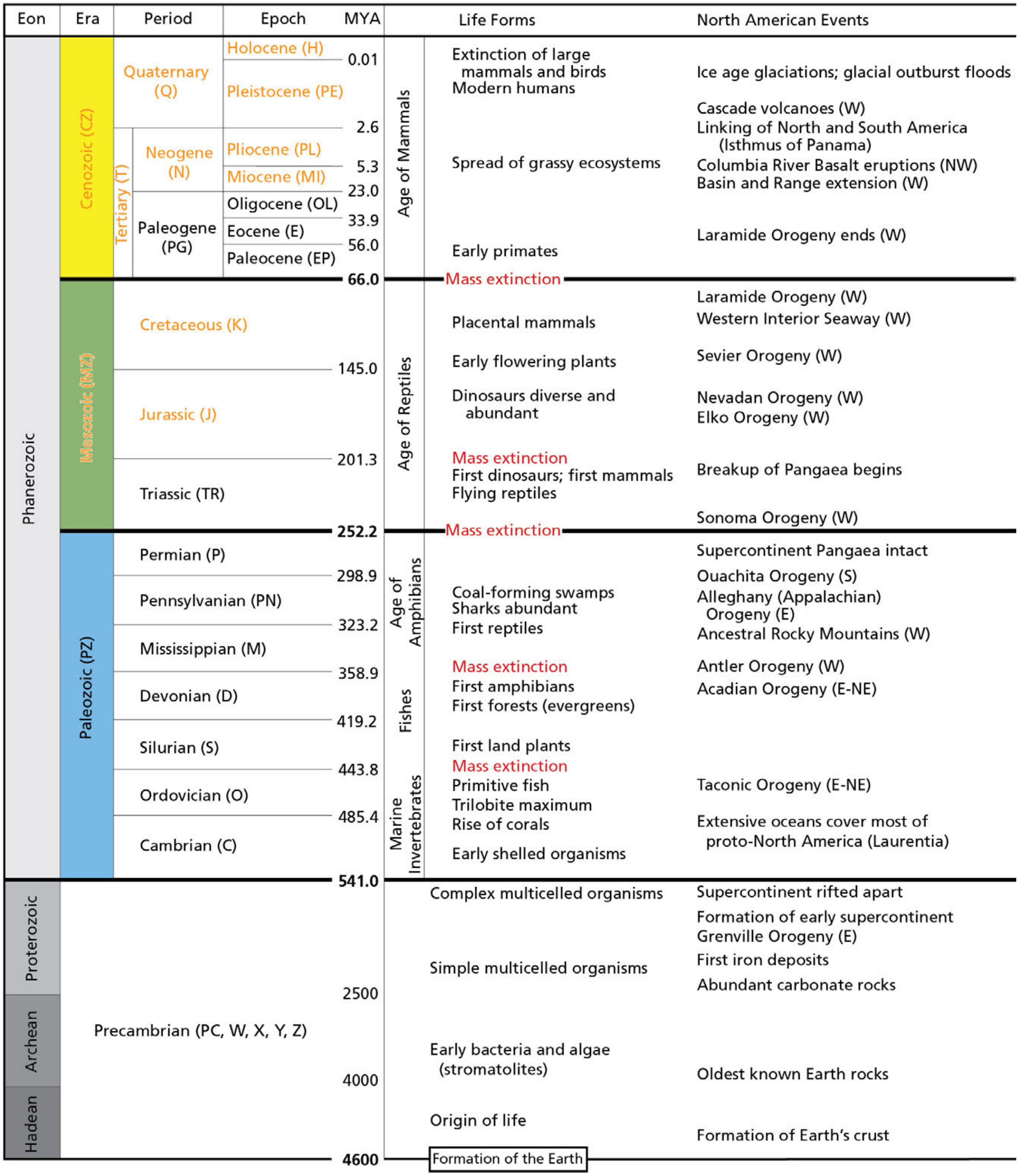

Figure 13. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. Geologic time divisions represented in the GRI GIS data are colored orange. GRI map abbreviations for each time division are in parentheses; rocks in the park are J (Jurassic), K (Cretaceous), T (Tertiary), and Q (Quaternary). Most of the rocks in the park are from the Miocene Epoch (MI). The Santa Monica Mountains formed during the Pliocene Epoch (PL); uplift is ongoing (Holocene Epoch [H]). Compass directions in parentheses indicate the regional locations of events. Boundary ages are millions of years ago (MYA). National Park Service graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale).

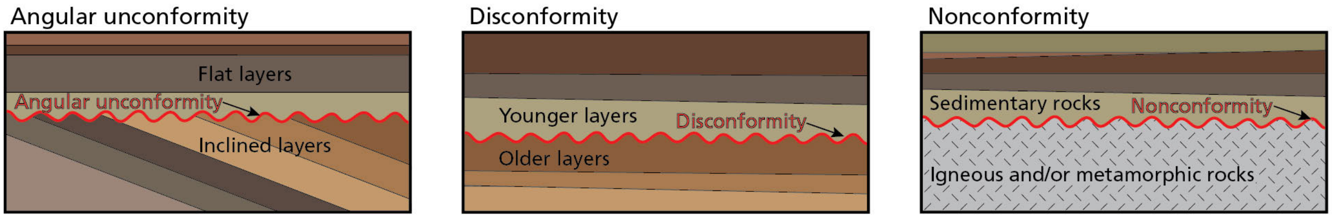

Figure 14. Graphic of unconformities. The rock record exposed in the park represents approximately 156 million years of geologic time, from the Jurassic Period to the present. This time span includes seven documented unconformities including five angular unconformities, one disconformity, and one nonconformity (see table 1). The red "wavy" line on the individual graphics indicates the unconformity. Notably, this is not how they look at an outcrop (see fig. 38). Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Lillie (2005, figure 2.4).

Runyon Canyon Erosion Surface

The angular unconformity at the base of the Simi Conglomerate (**Tsi**) in the park's rock record documents the time period between 75 million and 58 million years ago. Deep, tropical weathering took place on this unconformity (Fritsche and Weigand 2008). This distinctive erosion/weathering surface, referred to as the "Runyon Canyon erosion surface," and the Paleocene and Eocene sedimentary sequence of rocks overlying it are important geologic features that have been used to establish regional correlations between rock units and the tectonic history of the Transverse and the Peninsular ranges in southern California (Colburn and Novak 1989).

Significantly, the Runyon Canyon erosion surface coincides with the Cretaceous-Tertiary ("K-T") boundary that marks a massive, worldwide extinction event 66.0 million years ago (fig. 13). Now the boundary is formally referred to as the Cretaceous-Paleogene (K-Pg) boundary, though the traditional "K-T boundary" terminology is still in common usage. This boundary often captures the public's imagination because it resulted in a world without dinosaurs. An estimated 50% of all species, including dinosaurs, did not survive this extinction event. The accessibility of this significant boundary is also of public interest. Geologists have identified sites throughout the world, some near national parks (see GRI report about Capulin Volcano National Monument by KellerLynn 2015), where "boundary enthusiasts" can touch the surface. The boundary can be seen in several places in the Santa Monica Mountains (Colburn and Novak 1989), though not all of the sites are located within the park. Colburn and Novak (1989) provided sketch maps and descriptions of publically accessible sites within the Santa Monica Mountains such as Fryman Canyon Park in Santa Monica Mountains Conservancy and Runyon Canyon Park in the City of Los Angeles.

Rock Types

Geologists classify all rocks into three major types: (1) sedimentary, (2) igneous, and (3) metamorphic. The park has all three types. Of the 17 named formations exposed in the park, 14 are sedimentary, two are igneous, and one is metamorphic (see also "Formations" section). Table 1 provides a list of all the rocks in the park. Tables 2 and 3 summarize characteristics of sedimentary and igneous rocks, respectively.

Table 2. Clastic sedimentary rock classification and characteristics.

Rock Name	Clast Size	Local Depositional Environment	Examples in the Park*
Conglomerate (rounded clasts) or Breccia (angular clasts)	>2 mm (0.08 in) [larger]	Alluvial fan (higher energy)	Trabuco Formation
Sandstone	1/16–2 mm (0.0025–0.08 in)	Turbidite	Chatsworth Formation
Siltstone**	1/256–1/16 mm (0.00015–0.0025 in)	Marine or nearshore marine	Santa Susana Formation
Claystone**	<1/256 mm (0.00015 in) [smaller]	Submarine fan (lower energy)	Modelo Formation

*See table 1 for a listing of all sedimentary rock units in the park.

**Claystones and siltstones can also be called "mudstone," or if they break into thin layers, "shale."

Sedimentary Rocks

Sedimentary rocks are layered strata formed through the accumulation and solidification of sediments, which may consist of fragments of preexisting rocks, minerals, or animal or plant matter. The sediments that make up the rocks in the park were deposited in a variety of settings, from deep marine to nonmarine/terrestrial (table 1), though marine rocks prevail. Sediments that were deposited in marine settings millions of year ago now sit high in ridges and peaks of the park as a result of tectonic forces and the uplift. For example, the Topanga Canyon Formation ("**Ttc**" map units) makes up numerous summits and a distinctive anticline in the park (see "Folds" section; figs. 13 and 15). The Topanga Canyon Formation is highly fossiliferous and contains both marine and terrestrial fossils (see "Paleontological Resources" section) indicative of nearshore marine environments where fluvial activity also played a role. The formation consists of sandstone, commonly arkosic (feldspar-rich), with interbedded siltstone, pebbly sandstone, and pebble-cobble conglomerate (fig. 16).

Figure 15. Photograph of Saddle Peak. The Topanga Canyon Formation ("Ttc" map units; sandstone, siltstone, mudstone, and conglomerate) makes up Saddle Peak. During the last 4 million years, these rocks were uplifted from a former ocean floor and shoreline to 97 m (2,782 ft) above sea level today. Photograph by user "MiniHolland" available via Wikimedia Commons https://commons.wikimedia.org/wiki/File:Saddle_Peak,_California.JPG (Creative Commons Attribution-Share Alike 3.0 Unported [CC BY-SA 3.0]; https://creativecommons.org/licenses/by-sa/3.0/deed.en).

The Sespe Formation (**Ts** and **Tsp**) is the primary terrestrial formation in the park (figs. 16 and 17). It consists of a mostly nonmarine sequence of sandstone, pebbly sandstone, varicolored mudstone, and pebble-cobble conglomerate that was deposited by streams and

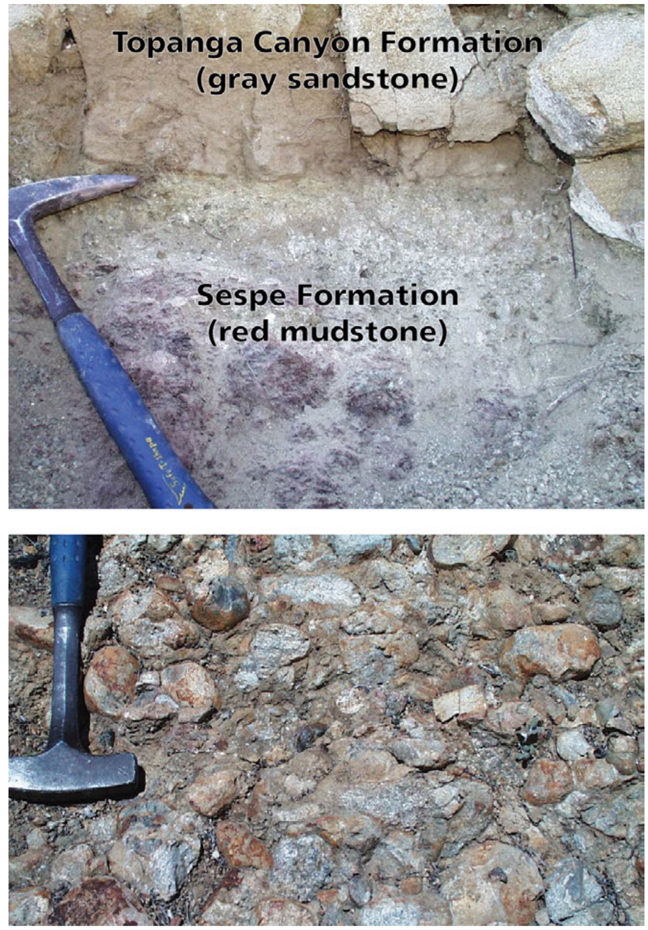

Figure 16. Photographs of the Topanga Canyon and Sespe Formations. In the upper photograph, the Topanga Canyon Formation (gray sandstone) was deposited on top of the Sespe Formation (red mudstone) in the central Santa Monica Mountains. The sequence of marine sandstone (Topanga Canyon Formation) over terrestrial sandstone (Sespe Formation) indicates a period of subsidence and transgression. In the lower photograph, conglomerate beds near the base of the Topanga Canyon Formation indicate deposition in a cobble beach environment where wave action was strong. The exposures in the both photographs are along the Calabasas Motorway just north of its junction with Red Rock Road. Rock hammers (total length approximately 28 cm [11 in]) for scale. Photographs from Eugene Fritsche (California State University, Northridge, Department of Geological Sciences, professor emeritus, GRI scoping presentation, 7 May 2008).

Figure 17. Photograph of the Sespe Formation. As shown in an exposure along Rambla Pacifico Road, the Sespe Formation commonly consists of river deposits such as the conglomerate. Elsewhere, the formation also has sandstone and mudstone layers. Rock hammer (total length approximately 28 cm [11 in]) for scale. Photograph from Eugene Fritsche (California State University, Northridge, Department of Geological Sciences, professor emeritus, GRI scoping presentation, 7 May 2008).

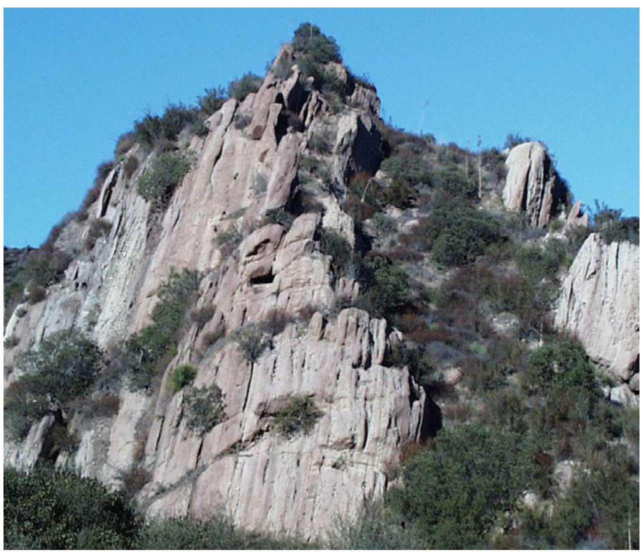

Figure 18. Photograph Red Rock Canyon Park. The red beds in Red Rock Canyon Park are composed of the Sespe Formation (Ts; sandstone, mudstone, and conglomerate), which is the primary terrestrial formation in the park. Photograph from Eugene Fritsche (California State University, Northridge, Department of Geological Sciences, professor emeritus, GRI scoping presentation, 7 May 2008).

rivers in channels, floodplains, and deltas. The lower Sespe Formation (**Ts**) is characterized by distinctive "red beds" in Red Rock Canyon Park (fig. 18). The sandstone beds are red chiefly due to the presence of ferric oxide (hematite) on the intergranular biotite mineral grains; not all beds have the characteristic red color. The Piuma Member (**Tsp**) is distinguished from

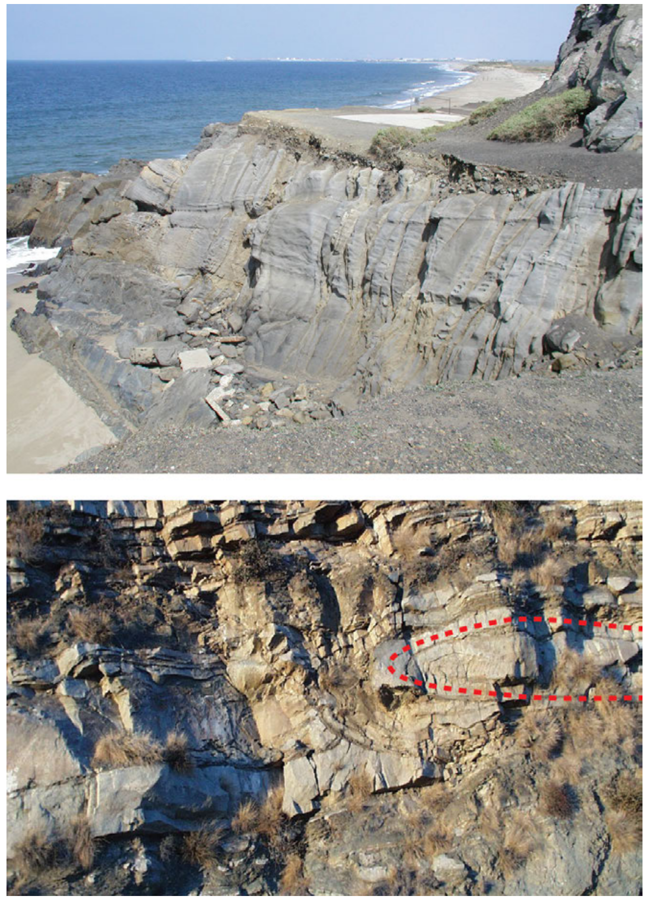

Figure 19. Photographs of the Vaqueros Formation. Shown in the upper photograph, the Vaqueros Formation crops out at Point Mugu. The thick, cross-bedded sandstone was deposited in a shallow marine environment. In the lower photograph, rolled over layers (dashed red line) in the sandstone formed because sand beds deposited on the ocean slope or on a submarine fan became unstable soon after deposition and slid downhill. The exposure in the lower photograph is in a road cut on the north side of Pacific Coast Highway about 0.8 km (0.5 mi) west of Point Mugu. Upper photograph by Katie KellerLynn (Colorado State University). Lower photograph from Eugene Fritsche (California State University, Northridge, Department of Geological Sciences, professor emeritus, GRI scoping presentation, 7 May 2008).

the lower Sespe Formation (**Ts**) by thinner individual beds, generally finer grained sandstone, the absence of pebble and cobble conglomerate, and greater abundance of interbedded lacustrine or lagoonal siltstone. Also, the Piuma Member intertongues with the Vaqueros Formation ("**Tv**" map units), a nearshore to offshore marine deposit. The Vaqueros Formation is a widespread, heterogeneous sequence of thick- and medium-bedded sandstone and interbedded siltstone and mudstone (fig. 19) that contains a distinctive molluscan fauna (see "Paleontological Resources" section). A transgressive–regressive cycle of fluvial, nonmarine delta, and shelf deposits resulted in the intertonguing of the Sespe Formation with the fossiliferous sandstone and mudstone of the Vaqueros Formation between 28 million and 21 million years ago (Fritsche and Weigand 2008).

Igneous Rocks

Igneous rocks formed from magma (molten rock material). Where they erupt onto Earth's surface, including the seafloor, they are considered "extrusive" (table 3). Where they intrude preexisting rocks in the subsurface, they are considered "intrusive." Although the term "volcanic" is sometimes used as a synonym for extrusive igneous rocks, "volcanic rocks" can include both extrusive rocks and shallow near-surface intrusive rocks related to a volcanic system.

The park has both intrusive and extrusive igneous rocks. The oldest igneous rocks in the park are intrusive; they consist of granitic rocks (**Kgr**; fig. 20) that were emplaced during the Cretaceous Period (fig. 13). These rocks are part of the Sierra Nevada–Peninsular Ranges magmatic arc. They intruded the Santa Monica Slate ("**Jsm**" map units; see "Metamorphic Rocks" section).

Notable extrusive igneous rocks in the park are the Conejo Volcanics ("**Tco**" map units), which cover a large

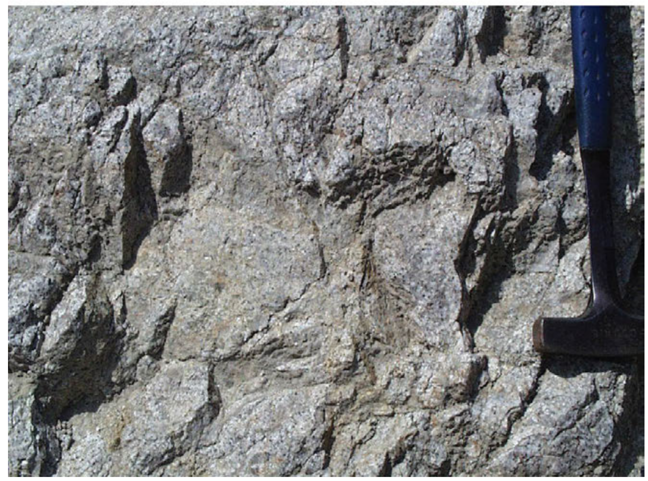

Figure 20. Photographs of granitic rocks. The light-colored granitic rocks (Kgr) exposed along the trails in the Griffith Park area intruded the Santa Monica Slate ("Jsm" map units) about 102 million years ago. The outcrop in the upper photograph is below Griffith Observatory. The close-up view of the rocks in the lower photograph is from a trail cut just south of the Griffith Park Observatory. Photographs from Eugene Fritsche (California State University, Northridge, Department of Geological Sciences, professor emeritus, GRI scoping presentation, 7 May 2008).

Table 3. Volcanic rock classification and characteristics.

Rock Name	Silica (SiO_2)*	Viscosity	Explosiveness	Rock Formations in the Park
Rhyolite	>72%			None
Rhyodacite	68%–72%			None
Dacite	63%–68%	Viscosity decreases from rhyolite (higher viscosity) to basalt (lower)	Explosiveness decreases from rhyolite (more explosive) to basalt (less explosive)	Conejo Volcanics; Zuma Volcanics
Andesite	57%–63%			Conejo Volcanics; Zuma Volcanics
Basaltic andesite	53%–57%			Conejo Volcanics
Basalt	<53%			Conejo Volcanics; Zuma Volcanics

*From Clynne and Muffler (2010).

Figure 21. Photographs of submarine features in the Conejo Volcanics. In the upper photograph, pillow-shaped masses of basalt are indicators that the lava erupted under water. These particular pillow basalts are exposed on Yerba Buena Road. In the lower photograph, oyster shells in the lava flows are further evidence of the submarine origin of the Conejo Volcanics. This exposure is in a road cut on Mulholland Highway, southeast of Malibu Creek State Park. Rock-hammer head (approximately 17 cm [7 in] long) for scale. Photographs from Eugene Fritsche (California State University, Northridge, Department of Geological Sciences, professor emeritus, GRI scoping presentation, 7 May 2008).

area of the western part of the Santa Monica Mountains (see "Conejo Volcanics" section). They generally consist of flows, breccias (consisting of angular, broken rock fragments), and tuffs (consolidated volcanic ash and larger particles), as well as related intrusive rocks. Separately mapped intrusive rocks (**Ti**, **Tid**, **Tia**, and **Tib**) and mixed rocks (**Tim**) in the central and western Santa Monica Mountains may also be related to the Conejo Volcanics and have formed dikes, sills, and plugs in the Topanga Canyon Formation. Zuma Volcanics (**Tz**), which are only exposed south of the Malibu Coast Fault, mainly consist of extrusive flows, flow breccias, and pillow lavas (pillow-shaped masses of lava formed in subaqueous environments).

Conejo Volcanics

The Conejo Volcanics erupted into a marine basin and built upwards from the seafloor into shield volcanoes. During the GRI scoping field trip, Eugene Fritsche (California State University Northridge) pointed out a cross section of a 17 million–15-million-year-old shield volcano near the intersection of Kanan Road and Agoura Road. Fritsche referred to the basal portion of this cross section as the "Bowels of Hades" or "Gates of Hell." This portion preserves the conduit through which molten rock flowed to the surface.

The Conejo Volcanics in the park contain evidence of both submarine and subaerial origins. The rocks contain lava flows with "pillows" and oyster beds (fig. 21; see "Paleontological Resources" section), which are indicative of an underwater setting. Lahars (mudflows on the flanks of a volcano) near the top of the Conejo Volcanics contain petrified logs (see Stadum and Weigand 1999) that indicate an elevation of at least 1,500 m (5,000 ft) above sea level (Eugene Fritsche, California State University, Northridge, Department of Geological Sciences, professor emeritus, GRI scoping presentation, 7 May 2008). The Conejo Volcanics also contain volcanic bombs (magma erupted into the air and shaped while in flight; "bombs" are more than 64 mm [2.5 in] across; fig. 22), which are indicative of subaerial deposition.

An unusual phenomenon in the Conejo Volcanics is the interbedding of calcareous sandstone and volcanic rocks (KellerLynn 2008; see "Paleontological Resources" section). Also, the Conejo Volcanics contain rare oil seeps (fig. 23). The oil probably migrated from older (underlying) marine sedimentary rocks (Pam Irvine, California Geological Survey, senior engineering geologist, conference call, 17 November 2015).

At 948 m (3,111 ft) above sea level, Sandstone Peak is the highest peak in the park (fig. 24). The peak's name is a geologic misnomer because the mountain is made up of Conejo Volcanics (igneous rocks) not sandstone (a sedimentary rock). The summit consists of the Conejo Volcanics, andesitic central zone (**Tcoa**), which is composed of andesitic flows, flow breccias, and

Figure 22. Photograph of volcanic bomb in the Conejo Volcanics. Near the top of the Conejo Volcanics, the presence of volcanic bombs—molten rock ejected into the air and shaped while in flight; "bombs" are more than 64 mm (2.5 in) across—indicates that the volcano was subaerial, rising above sea level as a volcanic island. This bomb is on Ladyface Mountain west of Kanan Road and south of Agoura Road. Lip-balm tube for scale. Photograph from Eugene Fritsche (California State University, Northridge, Department of Geological Sciences, professor emeritus, GRI scoping presentation, 7 May 2008).

Figure 23. Photograph of oil seeps in the Conejo Volcanics. Oil seeps are a rare but distinctive feature of the Conejo Volcanics at the park. The oil probably migrated from underlying marine sedimentary rocks. The estimated area covered by the tar seep in this photograph is 18 cm (7 in) wide by 30 cm (12 in) high. Photograph by Katie KellerLynn (Colorado State University).

Figure 24. Photograph of Sandstone Peak. At 108 m (3,111 ft) above sea level, Sandstone Peak is the highest point in the Santa Monica Mountains. Hikers can reach the summit via the Backbone Trail, starting at Circle X Ranch. The peak is composed of Conejo Volcanics, specifically andesitic volcanic rock, although its texture and appearance is similar to sandstone. Photograph by Flickr user "IvyMIke", available via Wikimedia Commons https://commons.wikimedia.org/wiki/File:Looking_at_Sandstone_Peak_from_Inspiration_Point.jpg (Creative Commons Attribution 2.0 Generic [CC BY 2.0]; https://creativecommons.org/licenses/by/2.0/deed.en).

agglomerate (volcanic breccia). However, the geologic description of the Conejo Volcanics refers to "volcanic sandstone" (see samo_geology.pdf in GRI GIS data). Furthermore, the breccia and agglomerate at the summit resemble sedimentary rocks (Pam Irvine, California Geological Survey, senior engineering geologist, written communication, 14 June 2016).

Metamorphic Rocks

Metamorphic rocks are those that have been metamorphosed (altered) by high temperature, pressure, or fluids. The oldest rocks in the park—Santa Monica Slate ("**Jsm**" map units)—are metamorphic (fig. 25). The dark gray rocks of the Santa Monica Slate are exposed in road cuts in the eastern part of the park. They were metamorphosed while being sutured to the margin of the North America continent in the Late Jurassic–Early Cretaceous periods and then later altered by contact metamorphism when they were intruded by granitic rocks (**Kgr**; fig. 20) approximately 102 million years ago (see "Geologic History" section).

Figure 25. Photographs of the Santa Monica Slate. The oldest rocks in the park are the metamorphic Santa Monica Slate ("Jsm" map units). The road cut in the upper photograph exposes the slate along the east side of I-405 opposite Mountaingate Drive. The dark-gray rocks in the road cut are the slate. The close-up view of the slate in the lower photograph is from an exposure in a road cut along the east side of Skirball Center Drive just south of its intersection with Mulholland Drive. Note lens cap in lower photograph for scale. Photographs from Eugene Fritsche (California State University, Northridge, Department of Geological Sciences, professor emeritus, GRI scoping presentation, 7 May 2008).

Formations

As shown in the GRI GIS data, the park contains 17 formally designated formations (table 1). Formations are fundamental rock-stratigraphic units and have the following attributes: they can be mapped at a regional scale; they are distinct from adjoining strata by features such as chemical or mineral composition, textures, or fossils; and they have definable upper and lower contacts.

Some of these formations were originally described and named from areas within or near the park (see "Type Sections" section). The rock formations north and south of the Malibu Coast Fault (see "Faults" section) represent distinctly different areas with respect to provenance and tectonic history (Yerkes and Campbell 1979) (see tables 1a and 1b and "Geologic History" section).

A formation may be combined with other formations to create a group. One formal group—the Topanga Group—has exposures in the park. These exposures consist of intrusive and extrusive volcanic rocks (**Ttb**) that intruded the undivided Topanga Group (**Tt**). The Calabasas Formation (**Tcb**), Conejo Volcanics (**Tco**), and Topanga Canyon Formation (**Ttc**) are the three formations formally assigned to the Topanga Group by Yerkes and Campbell (1979); they are exposed in the central and western Santa Monica Mountains. In the eastern Santa Monica Mountains, middle Miocene rocks with similar rock types and fossils have been informally divided into Topanga Group sandstone, siltstone, and conglomerate (**Ttss**, **Ttsl**, and **Ttcg**; see GRI GIS data) and the intrusive and extrusive volcanic rocks (**Ttb**).

A formation also may be divided into members. Geologists have divided the Calabasas, Topanga Canyon, Vaqueros, and Sespe formations into members (see samo_geology.pdf in the GRI GIS data).

Type Sections

The place where a rock formation is best exposed is referred to as a "type locality." More particularly, an outcrop may display the formation so well as to become a reference location referred to as "type section." Type localities and type sections have both scientific and educational significance and are commonly "stops" on geological field trips. Because type localities and type sections typically occur where a formation was originally described and named, they also may have historical significance. The names of many well-known geologists are linked with type sections and localities. Within the park, the names of USGS geologists Robert F. Yerkes and Russell H. Campbell are tied to most of the type localities (table 4).

Type sections for eight formations occur within the authorized boundary of the park (table 4), though the Coal Canyon Formation is now considered part of

Table 4. Type sections at Santa Monica Mountains National Recreation Area.

Age (millions of years ago)	Formation	Namesake	Type locality	Reference
Miocene (23.0–5.3)	Calabasas Formation	Calabasas Peak	Los Angeles County, exposures in Stokes Canyon, in sec. 3, T. 1 S., R. 17 W., 3 km (2 mi) west of Calabasas Peak	Yerkes and Campbell (1979)
Miocene (23.0–5.3)	Conejo Volcanics	"Conejo Mountains"—one of the most important centers of Miocene volcanism in California	Ventura County, exposures at the western end of the Santa Monica Mountains	Taliaferro (1924)
Miocene (23.0–5.3)	Topanga Canyon Formation	Topanga Canyon	Los Angeles County, road cuts on Old Topanga Road, in SW/4 sec. 35, T. 1 N., R. 17 W.	Yerkes and Campbell (1979)
Miocene (23.0–5.3)	Trancas Formation	Trancas Canyon	Los Angeles County, exposures near mouth of Trancas Canyon	Yerkes and Campbell (1979)
Miocene (23.0–5.3)	Zuma Volcanics	Zuma Canyon	Los Angeles County, exposures on west side of canyon about 4 km (2.5 mi) north of Point Dume	Yerkes and Campbell (1979)
Eocene (?) and Paleocene (66.0–33.9)	Coal Canyon Formation *Note: This formation is now considered part of the Santa Susana Formation.*	Carbon (formerly Coal) Canyon	Los Angeles County, exposures in S/2 secs. 22 and 27, T. 1 S., R. 17 W.	Yerkes and Campbell (1979)
Upper Cretaceous (100.5–66.0)	Tuna Canyon Formation	Tuna Canyon	Los Angeles County, exposures in sec. 30, T. 1 S., R. 16 W.	Yerkes and Campbell (1979)
Upper Jurassic (163.5–145.0)	Santa Monica Slate	Santa Monica Mountains	Extensive exposures east of Topanga Canyon, Los Angeles County	Hoots (1931)

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

the Santa Susana Formation (Campbell et al. 2014). Having so many type sections in a single NPS area is unusual. The high number of type localities within the park is probably associated with its complex tectonic history and position on an active plate boundary, which ensured that a wide variety of rock units were brought together and exposed (see "Geologic History" section).

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

Paleontological Resources

Santa Monica Mountains National Recreation Area is one of at least 263 parks with paleontological resources. The park contains one of the most extensive and diverse fossil records in the National Park System (Tweet et al. 2014). The park's foundation document (National Park Service 2015a) identified paleontological resources as an "other important resource or value." Noteworthy statistics for the park include 2,300 known fossil localities, 50 holotype fossils (a specimen used in describing a "new" species), and type (reference) specimens for at least 50 taxa—16 snails, 11 foraminifera, 7 seaweeds (4 brown algae and 3 red algae), 6 bivalves, 6 fish, 2 ammonites, and 2 crabs (Tweet et al. 2012; Vince Santucci, National Park Service, paleontologist, conference call, 17 November 2015; Justin Tweet, NPS Geologic Resources Division, paleontology technician, email communication, 8 December 2015). The two most noteworthy fossil localities in the Santa Monica Mountains are Old Topanga Canyon, where no less than 133 species have been identified, and the fossil-fish localities in the Modelo Formation (Koch et al. 2004). Resource management issues associated with fossils are discussed in the “Paleontological Resource Inventory, Monitoring, and Protection” section of this report.

Of the 17 formations exposed in the park (table 1), 16 are known to contain fossils, either in the park or elsewhere. Only the Trabuco Formation (**Ktr**) is not known to contain fossils. Fourteen of the formations exposed in the park have yielded fossils (see discussion below); the other two have the potential to yield fossils, though no fossil discoveries have been made to date. The ages of known and potential fossils range from the Late Jurassic Period to the Quaternary Period (fig. 13), representing a span of more than 150 million years. The rocks in the park have yielded the remains of vertebrates, invertebrates, plants, microfossils, and trace fossils. The most abundant fossils are invertebrates such as bivalves, cephalopods, and gastropods; the least abundant are plants and include leaf and kelp fossils, fossil wood, and pollen and spores samples. Fossil fish make up the majority of vertebrate material (National Park Service 2013).

The following are particularly noteworthy formations in the park with respect to paleontological resources:

- Topanga Canyon Formation (“**Ttc**” map units). This is one of the most fossiliferous formations in the park (fig. 26). It is a variable unit, deposited during two transgressive–regressive cycles (see “Transgressive–Regressive Cycles” section), with both marine and nonmarine deposition (Flack 1993) and both marine and nonmarine fossils. The formation has abundant marine fossils, especially mollusks (Koch et al. 2004), some of which are newly described species (Tweet et al. 2012). It has the remains of gastropods, bivalves, barnacles, crabs, echinoids, sharks and rays, ray-finned fish, sea lions, and whales (Lander 2011). Terrestrial fossils in the formation include land plants, small reptiles, and mammals (Lander 2011). Investigators have found exceptional samples of petrified wood from the Fernwood Member of the formation, for example, a log that is 15 m (50 ft) long, though not intact (John Alderson, Los Angeles County Museum, personal communication during scoping, 7 May 2008).
- Modelo Formation (“**Tm**” map units). This is one of the most outstanding fossiliferous formations in the park. It is best known for its fish fauna (fig. 27). The quality of preservation of these specimens is remarkable. According to GRI scoping participants, these fossil fish are comparable to those of the world-famous Green River Formation in Wyoming, Utah, and Colorado (KellerLynn 2008). Fossil Butte National Monument in Wyoming preserves and interprets the exquisite fossils of the Green River Formation (see GRI report by Graham 2012b).

Figure 26. Photographs of fossils from the Topanga Canyon Formation. The Topanga Canyon Formation (sandstone, siltstone, mudstone, and conglomerate) is the most fossiliferous rock unit in the park. It has abundant marine fossils, such as gastropods (snail, *Cancellaria* sp.; upper photograph) and bivalves (mussel, *Mytilus mathewsonii*; lower photograph), as well as terrestrial fossils. Scale is in centimeters. Photographs from Eugene Fritsche (California State University, Northridge, Department of Geological Sciences, professor emeritus, GRI scoping presentation, 7 May 2008).

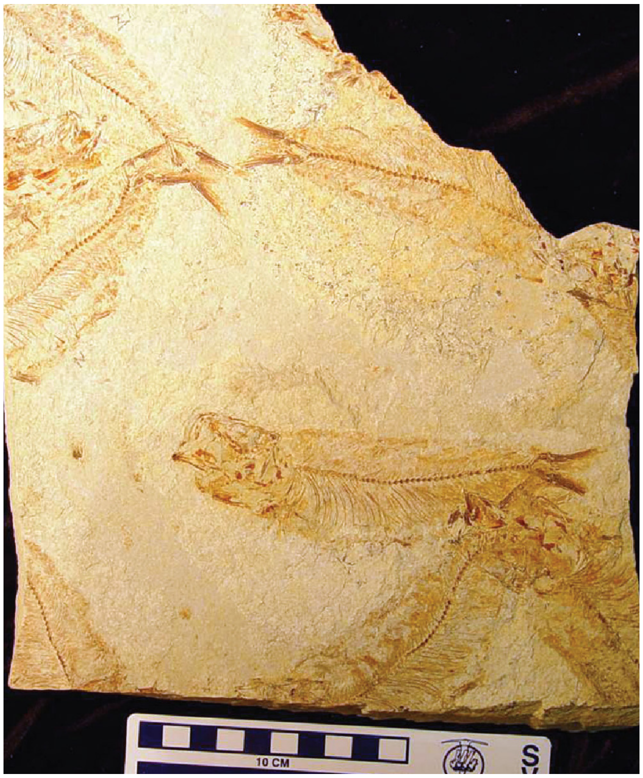

Figure 27. Photograph of fossil fish in the Modelo Formation. The most notable vertebrate fossils in the park are fish, such as *Xyne grex* (part of a subfamily of herring, sardines, and sprats), in the Modelo Formation (sandstone and shale). Scale is in centimeters. Photograph from Eugene Fritsche (California State University, Northridge, Department of Geological Sciences, professor emeritus, GRI scoping presentation, 7 May 2008).

- Sespe Formation (**Ts** and **Tsp**). Among a history of many marine rocks, the Sespe Formation stands out as the primary terrestrial formation in the park. Fossil discoveries from this formation in the park include both plants and animals: root casts, burrows, frogs, tortoises, didelphid marsupials (opossums), rodents, pikas, and camels (Whistler and Lander 2003; Lander 2011).
- Conejo Volcanics ("**Tco**" map units). Fossils in volcanic rocks are rare, yet within a small area of Malibu Canyon in the park, more than 200 fossil localities occur in the Conejo Volcanics (KellerLynn 2008). The formation is primarily composed of volcanic rocks such as basalt but is interbedded with sandstone, siltstone, and limestone. Fossils in the Conejo Volcanics include foraminifera, brachiopods, bivalves, gastropods, barnacles, echinoids, worm tubes, fish scales, and wood (fig. 21). These fossils are noteworthy because of the rarity of carbonate rocks in association with submarine volcanism as well as the rarity of limestone in the Cenozoic record of the Pacific Coast (Tweet et al. 2012).

In addition, the Tuna Canyon Formation ("**Kt**" map units), Chatsworth Formation (**Kc**), Simi Conglomerate (**Tsi**), Santa Susana Formation (**Tss** and **Tssl**), Llajas Formation (**Tl**), Vaqueros Formation ("**Tv**" map units; fig. 28), Zuma Volcanics (**Tz**), Calabasas Formation ("**Tcb**" map units), Trancas Formation ("**Tr**" map units), and Monterey Shale ("**Ttm**" map units) have yielded fossils in the park (Tweet et al. 2012). Although not a designated formation, sedimentary rocks of the Pacific Palisades area (**QTms**) have also yielded fossils (Pam Irvine, California Geological Survey, senior engineering geologist, written communication, 14 June 2016). The Santa Monica Slate ("**Jms**" map units) and Las Virgenes Sandstone (**Tlv**) have yet to yield fossils in the park but have potential based on discoveries outside the park. The most likely fossils to be found in the Santa Monica Slate are bivalves and ammonites. Logs, brackish water mollusks, and invertebrate burrows are the most likely fossils for the Las Virgenes Sandstone. The Trabuco Formation (**Ktr**) is not presently known to be fossiliferous. No fossils occur in the intrusive igneous rocks (**Kgr** and "**Ti**" map units) of the park (Tweet et al. 2012).

Figure 28. Photograph of the Vaqueros Formation. Fossil scallops in the Vaqueros Formation (sandstone, siltstone, and mudstone) at Point Mugu indicate deposition in a shallow-marine environment, approximately 28 million–21 million years ago. Pencil for scale. Photograph from Eugene Fritsche (California State University, Northridge, Department of Geological Sciences, professor emeritus, GRI scoping presentation, 7 May 2008).

Landslides

The park is located near the southern boundary of the Transverse Ranges, which compose a tectonically active area where uplift and extensive folding and faulting have produced many steep slopes of deformed and weakened rocks. These conditions have resulted in the widespread occurrence of landslides (Irvine and McCrink 2012). The hazards associated with landslides are discussed in the "Landslide Hazards" section of this report.

The term "landslide" refers to a wide variety of processes and landforms involving the downslope movement, under gravity, of masses of soil and rock material. Landslides have a broad range of morphology, rates, patterns of movement, and scale (fig. 29).

With respect to landslides within the park, the GRI GIS data (samo_geology.mxd) show only 12 occurrences of landslide deposits (**Qls**). Mapped landslide deposits occur mostly in Topanga State Park and north of Sequit Point and consist of rock detritus from bedrock and surficial materials, broken in varying degrees from relatively coherent large blocks to disaggregated small fragments. Most of these deposits are Holocene, though some dissected landslides may be as old as late Pleistocene.

Because only selected landslide deposits are shown in these data (samo_geology.mxd), this is only a small subset of the actual landslides on the landscape in the park. Landslide deposits (**Qls**) in these data were compiled primarily from landslide inventories prepared by the California Geological Survey for the Seismic Hazard Zonation Program. Only landslides described as definite or probable and larger than 50,000 m^2 (538,000 ft^2 or 12 ac) are shown to preserve the clarity of the underlying bedrock geology. Selected historically active landslides between 10,000 m^2 (108,000 ft^2 or 2 ac) and 50,000 m^2 are shown, but no landslides smaller than 10,000 m^2 are shown on this map. Exceptions to these rules include small or questionable landslides surrounded by larger probable or definite landslides (Campbell et al. 2014).

Significantly, the GRI GIS data set for the park also includes a separate ArcMap document file (samo_geohazards.mxd) and geodatabase (see "Geologic Map Data" section) of the locations of 3,580 landslides from a landslide inventory prepared by the California Geological Survey (Irvine and McCrink 2012). These landslide data only include features that were large enough to show as polygons at a scale of 1:24,000 (1 inch = 2,000 feet). Therefore, numerous smaller landslides exist but were too small to include in the database (Pam Irvine, California Geological Survey, senior engineering geologist, written communication, 11 May 2016). Also, the landslide inventory is ongoing (see "Landslide Hazards" section).

Of the 3,580 landslides in the GRI GIS data, 2,503 were mapped within the park. Based on the type of material and movement exhibited, landslide deposits may be categorized into types (fig. 29). The types of landslides in the park are, in order of prevalence, rockslide (2,039), debris slide (400), debris flow (31), rockfall (22), earthflow (8), debris spread (2), and rock flow (1). Notably, the California Geological Survey uses a modified version of the classification shown in figure 29.

Rockslides, the most prevalent type in the park, involve sliding bedrock that moved but remained largely intact. Debris slides, the second most prevalent type in the park, initially move as a shallow intact slab of material but break up after short distances into "falls" and "flows" (discussed below). Debris slides consist of coarse-grained soil, mostly in unconsolidated sandy or gravelly units but also in residual soils that form in-place from the weathering of bedrock. Falls are masses of soil or rock that dislodge from steep slopes and free fall, bounce, or roll downslope. Flows mobilize as a deforming, viscous mass without a discrete failure plane (a zone of weakness at the base of a rock mass where movement typically takes place).

In the park, rockslides and debris slides are most abundant in Tertiary-age sedimentary rocks that have been deformed by folding and faulting or contain weak clay layers (Irvine and McCrink 2012). Irvine and McCrink (2012) provided further information about these two types of landslides, as well as descriptions of the other types of landslides in the park. These descriptions are included in the ancillary map information document (samo_geology.pdf) for the GRI GIS data.

Fluvial Features

Malibu, Solstice, and Topanga creeks are perennial streams that flow in the park. Other streams have segments that are perennial. Runoff from developed areas creates unnatural streams and a perennial source of surface water (KellerLynn 2008).

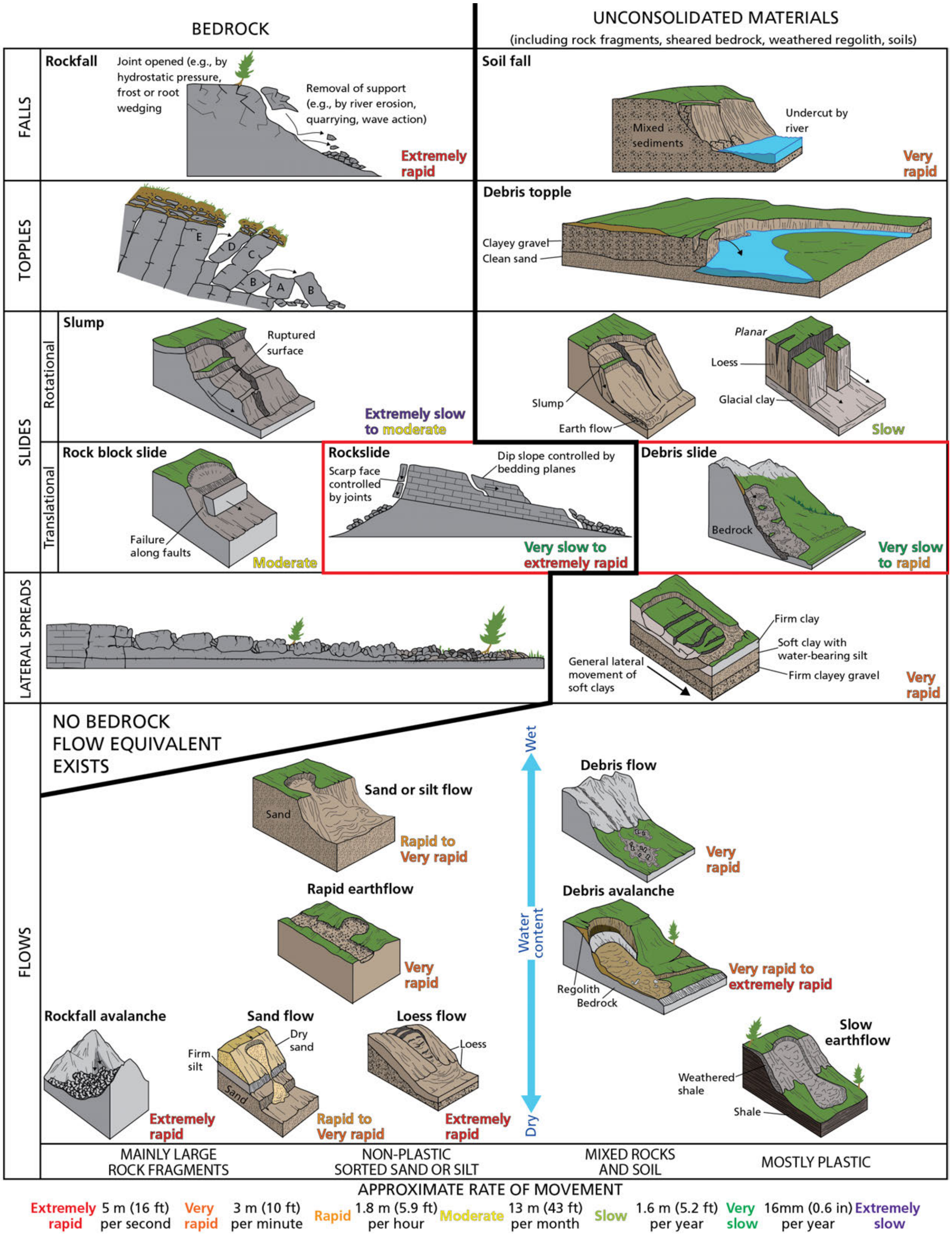

Figure 29. Graphic showing slope movements. Different types of slope movement are defined by material, nature of the movement, rate of the movement, and moisture content. Rockslides followed by debris slides (red boxes on graphic) are the most prevalent types of landslide in the park. The California Geological Survey uses a modified version of this classification, as do the GRI GIS data. Graphic by Trista Thornberry-Ehrlich (Colorado State University) redrafted using a graphic and information in Varnes (1978). Rates of movement are from Cruden and Varnes (1996).

Alluvium marks active, intermittent, and past streams, ranging in age from Pleistocene to Holocene (table 1 and fig. 13). Map units associated with fluvial activity include alluvium (**Qa**), young alluvium ("**Qya**" map units), and old alluvium (**Qoa**). Mappers divided the alluvial deposits in the park based on age. Alluvium (**Qa**; late Holocene Epoch) is the youngest and locally encompasses areas of historic flooding, including deposits behind flood-control structures. Young alluvium (**Qya**, **Qya2**, and **Qya1**; Holocene and late Pleistocene epochs) consists of unconsolidated, generally friable, stream-deposited silt, sand, and gravel on floodplains, locally including related alluvial fans and streambeds where those were not mapped separately. Deposits of young alluvium are clearly related to depositional processes that are still ongoing. Deposits of old alluvium (**Qoa**; late to middle Pleistocene Epoch) may be dissected to varying degrees or have soil development; these deposits have been uplifted or otherwise removed from active sedimentation in stream channels.

Cave and Karst Resources

Santa Monica Mountains National Recreation Area is one of at least 160 parks with caves and/or karst resources in the National Park System. Caves are naturally occurring underground voids such as solutional caves (commonly associated with karst), lava tubes (tunnel-like caves in a lava flow after lava has stopped flowing), sea caves (clefts or cavities in a sea cliff), talus caves (a void among collapsed boulders), regolith caves (formed by soil piping), and glacier caves (ice-walled caves) (Toomey 2009). Known caves in the park include sandstone caves in the Topanga Canyon ("**Ttc**" map units), Sespe (**Ts** and **Tsp**), and Chatsworth (**Kc**) formations. These caves are erosional features scattered throughout the park. Eagle Rock, Eagle Springs, and Garapito Canyon are notable areas with sandstone caves (KellerLynn 2008). In addition, where subjected to continuous wave action, sea caves have formed in several locations of rocky points along the ocean front in the park (Dale Pate, NPS Geologic Resources Division, National Cave and Karst Program Manager, written communication, 10 December 2015).

A popular hiking destination in the park is the Grotto at Circle X Ranch. Scoping participants noted that a stream runs through and around the Grotto, and online photographs commonly show a waterfall cascading over the entrance area. Scoping participants did not identify the Grotto as a significant cave feature (KellerLynn 2008), and not much is known about its geology. Based on online photographs, however, it appears to be a talus-type cave; it probably occurs in Conejo Volcanics (see GRI GIS data).

North of the park, the Simi Hills contain many small caves and rock shelters (KellerLynn 2008). Although these caves are outside the park, they are of interest to park managers as significant cultural sites, which have been highlighted in archeological studies and reports. The Simi Hills' caves and rock shelters are within the extent of the GRI GIS data.

The "Bat Cave" of Batman and Robin fame is in the park. It consists of a tunnel in an old quarry near Hollywood; it is not a natural cave and would, therefore, not be included in a cave resource inventory (see "Cave and Karst Resource Management" section). However, this feature is of interest for the park's film-making history, which merited a significance statement in the park's foundation document (National Park Service 2015a).

Karst is a landscape that forms through the dissolution of soluble rocks, commonly carbonate rocks such as limestone or dolomite (Toomey 2009). In the park, the Santa Susana Formation (**Tss** and **Tssl**), which is primarily shale, contains scattered pods and lenses of algal limestone and gray limestone concretions (hard, compact nodules). Also, the Fernwood Member of the Topanga Canyon Formation (**Ttcf**), which is predominantly sandstone, contains minor amounts of limestone. Neither formation has sink holes, caves, or other characteristic features of karst landscapes (Pam Irvine, California Geological Survey, senior engineering geologist, email communication, 17 November 2015). Nevertheless, smaller amounts of limestone [e.g., in pods and lenses] can still have active karst processes [e.g., groundwater discharge, recharge, and flow] (Dale Pate, NPS Geologic Resources Division, National Cave and Karst Program Manager, written communication, 10 December 2015).

Eolian Features and Processes

Eolian (also spelled "aeolian") refers to windblown erosion, transportation, and deposition of sediments (Lancaster 2009). Features created by eolian processes include depositional landforms and deposits such as dunes, loess, and sand sheets, as well as erosional forms such as desert pavement, yardangs, and ventifacts.

Figure 30. Photograph of the Great Dune. The "Great Dune" is the most notable eolian feature in the park. It is located along the Pacific Coast Highway south of Point Mugu. Note cars for scale. California Coastal Records Project, Image 200405486, taken 23 October 2004; http://www.californiacoastline.org/cgi-bin/image.cgi?image=200405486&mode=sequential&flags=0&year=2004. Copyright © 2002-2016 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org.

The GRI GIS data include eolian deposits (**Qe**). These consist of loose, fine- to medium-grained sand, silty sand, and silt along the coastline of the park. This material forms transitory dunes against beach-facing cliffs.

The "Great Dune" is the only "charismatic" eolian feature in the area. The dune, which is about 120 m (400 ft) tall, is a popular recreation destination (Barlow 2011). It is about 3.5 km (2.2 mi) south of Point Mugu along the Pacific Coast Highway and covers an area of roughly 50,639 m^2 (545,074 ft^2 or 13 ac) (fig. 30). Compared to sand dunes in other NPS areas (e.g., see GRI reports about Great Sand Dunes National Park and White Sands National Monument by Graham 2006 and KellerLynn 2012, respectively), this dune is not of huge dimensions, but it is the only one of any size in the park and is a good example of ongoing eolian processes (KellerLynn 2008).

Marine and Coastal Resources

The park's boundary stops at mean high water, so marine resources are minimal compared to other NPS areas such as Virgin Islands National Park (see GRI report by Hall and KellerLynn 2010), Buck Island Reef National Monument (see GRI report by KellerLynn 2011), and Dry Tortugas National Park (see GRI report by Port 2014), which are known for their reefs. Golden Gate National Recreation Area near San Francisco (see GRI report by Port 2016) contains marine areas.

Shipwrecks and kelp forests are notable submerged resources off the coast in the Santa Monica Mountains area, but the National Park Service has no management obligations at these locations. According to scoping participants, submarine canyons are of interpretive interest (KellerLynn 2008); for instance, the west end of Mugu Canyon is one of deepest submarine canyons off the coast of North America. Also, the only natural deep-water port between San Diego and San Francisco is located at Port Hueneme, approximately 11 km (7 mi) northwest of Point Mugu.

Coastal resources are located in a transition zone between marine and terrestrial environments and include characteristics of both. Coastal environments—shaped by wind, waves, tides, and weathering—may include tidal flats, estuaries, river deltas, wetlands, dunes, beaches, barrier islands, bluffs, headlands, and rocky tide pools. Coastal processes include both erosion as evidenced by wave-cut cliffs, sea caves (see "Cave and Karst Resources"), and other features (e.g., an arch in the park), and accretion, as evidenced by beaches.

The Santa Monica Mountains are known for sand and cobble beaches. Beach deposits (**Qb**) are more-or-less continuous along the 64-km (40-mi) coastline in the park, from Point Mugu to Santa Monica Pier (figs. 1 and 31). The GRI GIS data also include active coastal estuarine deposits (**Qes**), primarily landward of Laguna Point and surrounding Mugu Lagoon. These deposits occur where a coastal body of water meets the current of a stream. The authorized boundary of the park also contains rocky intertidal areas with tide pools and coastal lagoons (e.g., Malibu, Topanga, and Zuma).

The GRI GIS data include old shallow marine deposits on wave-cut surface (**Qom**). As an indication of age, some wave-cut surfaces show slight to moderate soil development. Moreover, overlying deposits locally contain molluscan fauna of the late Pleistocene Epoch (Addicott 1964).

Erosion of the shoreline produced these wave-cut platforms in bedrock, which were later covered by sedimentary deposits such as sand, silty sand, and gravel of nearshore marine, beach, estuarine, lagoonal, or continental dune origins. These features are the equivalent of marine terraces, representing abandoned strips of coastline at two or more altitudes above present sea level. The old shallow marine deposits on wave-cut surface (**Qom**) in the park have not been correlated to the prominent marine terraces in the area, of which there are two: (1) the higher, older Malibu Terrace (Davis 1933; Birkeland 1972); and (2) the lower, younger Point Dume (or Pacific Palisades) Terrace (McGill 1989). The Malibu Terrace formed about 320,000 years ago when sea level was 4 m (13 ft) higher than at present. The Point Dume Terrace formed about 125,000 years ago when sea level was about 6 m (20 ft) higher than at present (Shaller and Heron 2004). An intermediate terrace, the Corral Terrace, formed about 200,000 years ago when sea level was nearly the same as present (Shaller and Heron 2004). Although the Point Dume Terrace formed under conditions of higher sea level, referred to as a "highstand," than the Malibu Terrace, the Malibu Terrace is higher today because of uplift that occurred between the two highstands (Tweet et al. 2012). Because of tilting and uplift over the past 320,000 years, the terraces are not found at consistent elevations. For example, the Point Dume Terrace is at sea level west of Point Dume but about 90 m (300 ft) above sea level to the east (Soper 1938).

As climate continues to change, sea level rise is a major concern for coastal resources within the park. See "Climate Change Planning and Sea Level Rise" section.

Figure 31 (right). Photographs of coastline in Santa Monica Mountains National Recreation Area. The park stretches from roughly Point Mugu (upper photograph) past Point Dume (middle photograph) to Santa Monica Pier (lower photograph), spanning 64 km (40 mi) along the Pacific Ocean and Santa Monica Bay. The park's coastline has very different morphology and geology, depending on a specific location. Upper: The Vaqueros Formation (Tvd; siltstone or mudstone) is exposed at Point Mugu. Middle: The Monterey Shale (Tmt) crops out at Point Dume. Lower: Beach deposits (Qb; sand) were mapped at Santa Monica Pier. California Coastal Records Project, Image 8705162, taken June 1987, http://www.large.images.californiacoastline.org/images/1987/large/2/8705162.JPG; Image 8129, taken 30 October 2002, http://www.large.images.californiacoastline.org/images/2002/large/9/8129.JPG; and Image 200802289, taken 18 September 2008, http://www.californiacoastline.org/cgi-bin/image.cgi?image=200802289&mode=sequential&flags=0&year=2008. Copyright © 2002-2016 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org.

Geologic Resource Management Issues

This section describes geologic features, processes, or human activities that may require management for visitor safety, protection of infrastructure, and preservation of natural and cultural resources in Santa Monica Mountains National Recreation Area. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

During the 2008 scoping meeting (see scoping summary by KellerLynn 2008) and 2015 conference call, participants (see Appendix A) identified the following geologic resource management issues. They are ordered with respect to management priority.

- Landslide Hazards
- Paleontological Resource Inventory, Monitoring, and Protection
- Climate Change Planning
- Earthquakes
- Cave and Karst Resource Management
- Flooding and Dam Failure
- Abandoned Mineral Lands and Other Disturbed Lands

Resource managers may find *Geological Monitoring* (Young and Norby 2009) useful for addressing some of these geologic resource management issues. An online version of *Geological Monitoring* is available at http://go.nps.gov/geomonitoring. The manual provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. Each chapter covers a different geologic resource and includes detailed recommendations for resource managers, suggested methods of monitoring, and case studies.

Landslide Hazards

The GRI GIS data provide evidence of the Santa Monica Mountains' susceptibility to landslides. The data show the ubiquitous nature of landslides (fig. 32) with 3,580 geohazard features marked as both point features (symbols) and area features (colored polygons). Scoping participants noted that landslides pose a significant threat to park infrastructure and human safety. Big, deep landslides destroy roads; small quick landslides kill people (KellerLynn 2008).

In actuality, even more landslides than those included in the GRI GIS data occur on the landscape: smaller features were not mapped by Irvine and McCrink 2012; scale 1:24,000), and the landslide inventory by the California Geological Survey is ongoing (see "Landslides" section). Since the 2012 inventory, more landslides, especially along highways, have been added to the California Geological Survey's landslide database (GRI conference call participants, 17 November 2015). The database is now available at http://maps.conservation.ca.gov/cgs/lsi/. Updates include additional existing maps and new landslides. Sources of new landslides are aerial photos (e.g., from post-fire overflights), notable events covered by the media, locally reported failures (e.g., from the Ventura County geologist), and updates from geoengineering consultants tasked with mitigating hazards (GRI conference call participants, 17 November 2015).

Generally speaking, weak rocks such as shale and claystone; unconsolidated deposits, including artificial fill; and past landslide deposits are susceptible to landslides. Steep slopes add to the susceptibility of an area. Additionally, anthropogenic alteration of the landscape such as roads (e.g., undercutting a landslide deposit), other infrastructure (adding weight to a deposit), or irrigation (adding moisture) can affect slope, increasing its susceptibility to landslides. Also, earthquakes and storms can trigger landslides, and fire can denude vegetation, increasing susceptibility to landslides (see "Earthquakes" and "Climate Change Planning" sections). The State of California, Department of Conservation, provides an online map service at http://maps.conservation.ca.gov/cgs/firelandslide/ that shows fire perimeter and deep landslide susceptibility (fig. 33). This map service was based on work by Wills et al. (2011).

In addition to the GRI GIS data, sources of landslide information specific to the park include Steensen (2005), which is a trip report summarizing reconnaissance of unstable slopes and erosional features following winter 2004–2005 when record-setting precipitation in southern California initiated numerous landslides and erosional events; the GRI scoping summary (KellerLynn 2008); and a geologic

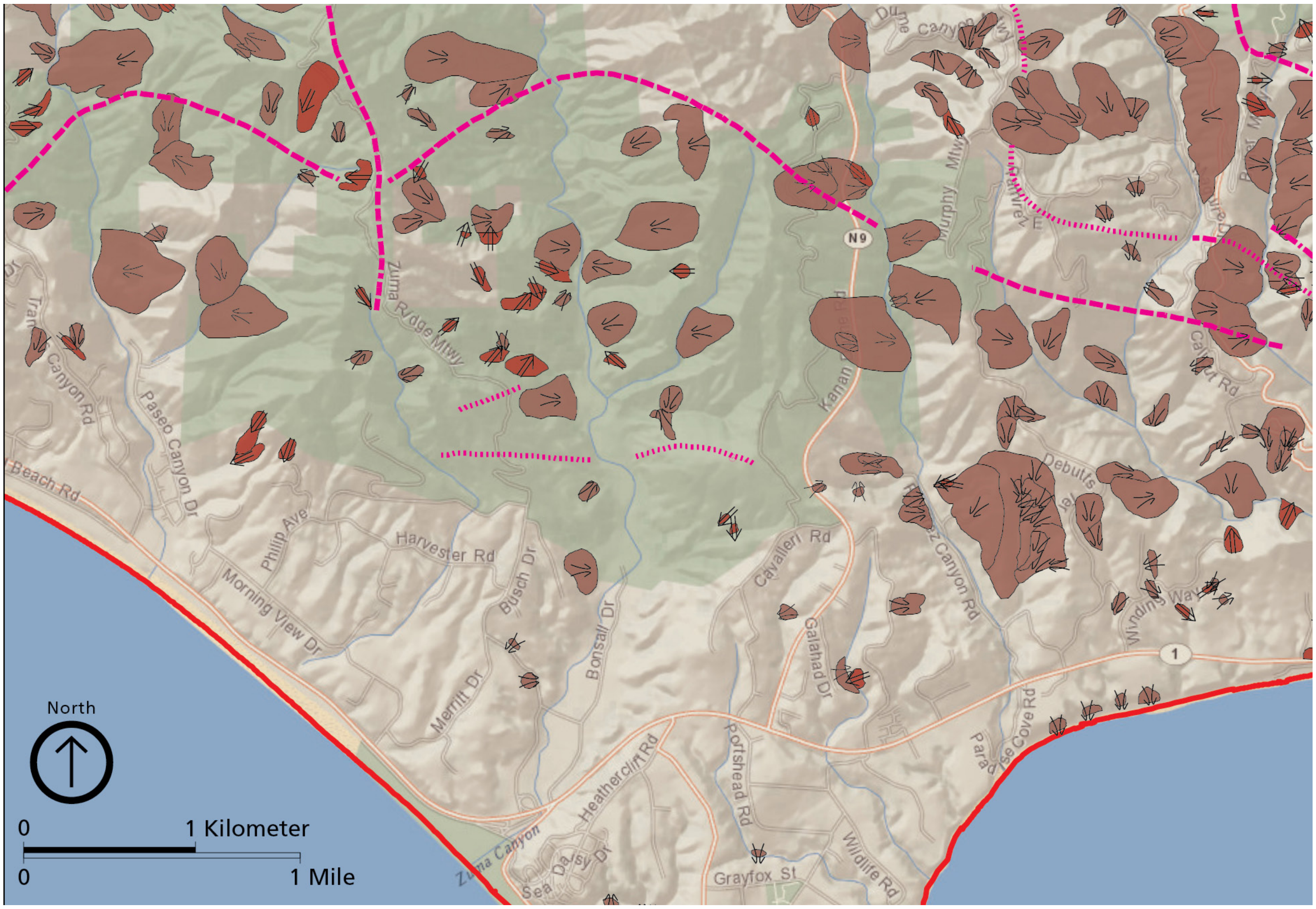

Figure 32. Portion of GRI GIS data showing landslides. The GRI GIS data (see samo_geohazards.mxd) contain 3,580 hazard area features that delineate past landslides throughout the park and vicinity. The brown and red forms on the graphic represent rockslides and soil slides in the Zuma Canyon area. The arrows point in the direction of flow. The hottest color (red) indicates the most recent activity. The labels are map symbols of various rock formations and unconsolidated deposits (see table 1 and GRI GIS data). The pink lines are anticlines and synclines. The red line is the park boundary. Data are plotted over ESRI National Geographic basemap layer. Sources: National Geographic, Esri, DeLorme, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp.

resources foundation summary (National Park Service 2013). Helpful online resources are listed in the "Additional References" section of this report. Scoping participants suggested the following resources:

- Campbell (1975) is USGS Professional Paper 851. Scoping participants identified this publication as a significant source of information about slope movements at the park.
- Highland and Bobrowsky (2008) is a "landslide handbook" published by the US Geological Survey.
- Wieczorek and Snyder (2009)—the *Geological Monitoring* chapter about slope movements—described five vital signs for understanding and monitoring slope movements: (1) types of landslide, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessment of landslide hazards and risks.
- Work by Susan H. Cannon at the US Geological Survey is applicable to the park. Reports can be found by searching "Susan Cannon" on the USGS Publications Warehouse at https://pubs.er.usgs.gov/. Although Cannon has recently retired, the US Geological Survey continues work on the cycle of landsliding and fires in California; for example, Dennis Staley is conducting research in the park (Conference call, 17 November 2015).

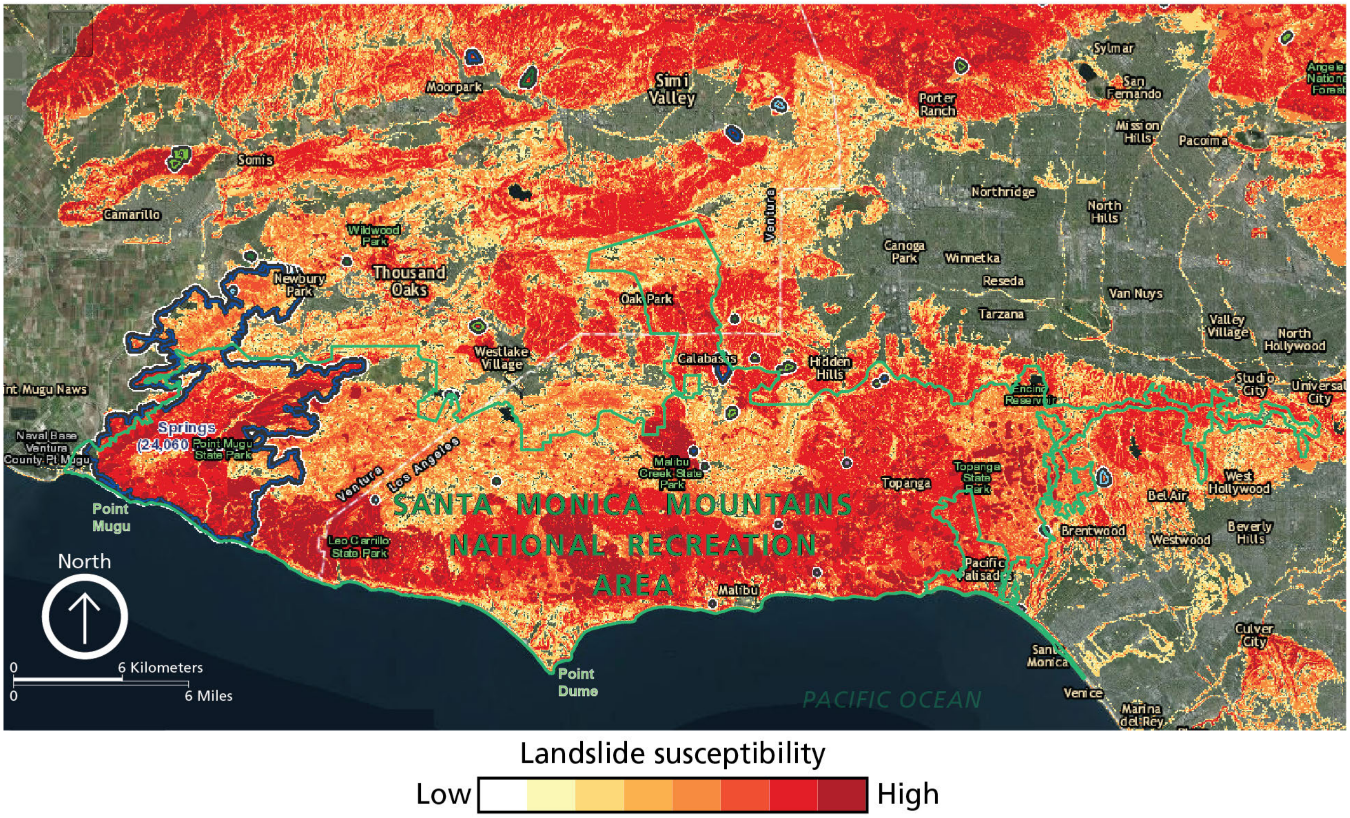

Figure 33. Screen capture of map service showing fire perimeter and landslide susceptibility. Two factors are important for reading this map: (1) weak rocks and steep slopes are more susceptible to landslides, and (2) recent wildfires increase the likelihood of landslides. The white to dark-red areas indicate susceptibility to deep landslides. Darker reds have a higher susceptibility. Many areas in the park are highly susceptible. Recent fires are outlined in blue (see the legend at http://maps.conservation.ca.gov/cgs/firelandslide/); for example, the area of the 2013 Spring Fire at the western edge of the park. That fire covered 9,740 ha (24,060 ac).

Paleontological Resource Inventory, Monitoring, and Protection

All paleontological resources are nonrenewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act (see Appendix B). As of August 2016, National Park Service regulations associated with this act had been signed. Regulations for other agencies in the Department of Interior were awaiting signatures.

The variety of landowners and management strategies within the park highlight the need for the development of a resource stewardship strategy for paleontological resources that would contain specific management guidance, as well as a visitor use management plan. These needs were identified in the park's foundation document (National Park Service 2015a). In addition, the foundation document identified the need for an inventory of fossil locations in the park's GIS.

Documentation of fossil localities is necessary for evaluating their accessibility as it relates to protection from potential theft as well as a site's worthiness for interpretation and visitors' ability to access it. Such an inventory is the first step in assessing a locality's condition and determining an appropriate monitoring plan.

Inventory

With respect to inventorying the park's paleontological resources, Tweet et al. (2012) provided a list of relevant publications for the Santa Monica Mountains. Investigators have been collecting, studying, and describing these paleontological resources since 1906, and opportunities abound for continued paleontological research and collaboration with nearby universities as well as partnerships and public outreach with the Natural History Museum of Los Angeles County and the La Brea Tar Pits (National Park Service 2015a).

Three NPS publications provide park-specific information: Koch and Santucci (2003), Koch et al. (2004), and Tweet et al. (2012) (see "Literature Cited" section). Also, a paper by Tweet et al. (2014) summarized these NPS publications and provided more recent findings. Of significance for resource management and inclusion in the park's GIS, Hoots (1931) documented many of the known fossil localities (KellerLynn 2008).

Monitoring

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 identified threats (discussed below). Park managers are encouraged to contact the NPS Geologic Resources Division for assistance.

Protection

Varying access and land management regulations throughout the park likely contribute to confusion over fossil collecting prohibitions and research permit requirements. Furthermore, with increasing recreational use comes an increased potential for illegal fossil collecting within the park.

The park's foundation document (National Park Service 2015a) listed the following three threats to the park's paleontological resources:

- Illegal amateur fossil collecting is a major threat to the preservation of the paleontological history. The removal of fossils happens on a recurring basis in all areas of the mountains, even those not governed by the National Park Service. More fossiliferous locations in the surrounding area should be protected by the National Park Service, state parks, or the Mountains Recreation and Conservation Authority in order to prevent any further removal.
- Natural erosion of the landscape can impact the preservation of the fossils in several sites.
- Graffiti is becoming a major threat to the paleontological resources.

Similarly, Tweet et al. (2014) noted coastal and mountain erosion, landslides, theft, and vandalism as threats. Koch et al. (2004) reported that many of the fossil fish localities in the Modelo Formation have been destroyed or made inaccessible as a result of private construction.

Visitor use and access is a "key issue" identified in the park's foundation document (National Park Service 2015a). The variety of land owners, and associated management priorities, within the park's authorized boundary highlights the interrelationship between a key issue (visitor use and access) and an important resource and value (paleontological resources). These issues are also related to stressors—housing development, road distance and accessibility, and human footprint—identified in the park's natural resource condition assessment (Stoms et al. 2013).

Interpretation

The local community has roots in fossil collecting since the 1930s, with many adults maintaining their enthusiasm for fossils from childhood visits to the Old Topanga Canyon fossil locality (Koch et al. 2004). Opportunities for interpretation abound in a park with a wealth of paleontological resources (see "Paleontological Resources" section) to a public with a long-term interest. Significantly, however, the Old Topanga Canyon fossil locality is privately owned, and visitors are not presently allowed on the property (National Park Service 2015a). Similarly, access and the lack of visitor infrastructure are issues for Fossil Ridge Park, another important fossil locality in the Santa Monica Mountains. Thus past practices and the patchwork of land ownership in the Santa Monica Mountains are likely to cause confusion about which fossil localities can be accessed and/or where fossil collecting is allowed.

As with all National Park Service areas, fossil collecting is prohibited in the park. Also, researchers need to acquire permits for paleontological investigation and collection within the park. These regulations, however, may not be common knowledge. Consequently, fossil-focused public outreach and education by the National Park Service and its management partners in Santa Monica Mountains Recreation Area should include a clear discussion about fossil resource management regulations for the different areas and landowners. Park managers are encouraged to contact the NPS Geologic Resources Division about developing an interpretive message.

Recommendations

Koch et al. (2004) made the following recommendations: (1) conduct active resource management at Old Topanga Canyon fossil site; (2) promote research, particularly at the Old Topanga Canyon site, the Modelo fossil fish beds, and fossil wood deposits; (3) patrol known sites; (4) continue cooperation with state parks, conservancies, museums, and universities; (5) develop a Project Management Information System (PMIS) statement for fossil resource protection; (6) assess the commercial value of fossils preserved within the park; (7) provide training for park staff in fossil resource protection; and (8) increase public awareness of NPS fossil regulations. Tweet et al. (2012) recommended that these recommendations in Koch et al. (2004) be reviewed in order to check progress and determine if any should be modified or dropped. In addition, Tweet et al. (2012) made the following recommendations: (1) monitor significant sites at least once per year; (2) compile a list and contact local researchers, perhaps annually, for assistance in evaluating new discoveries and keeping park staff up-to-date on recent discoveries; (3) encourage park staff members to observe exposed sedimentary rocks and associated eroded deposits for fossil material while conducting their usual duties, and photodocumenting and monitoring any occurrences of in situ paleontological resources; (4) encourage park staff to take part in paleontological field trips with trained paleontologists; (5) schedule site monitoring by a trained paleontologist during future construction projects or archeological excavations in order to document and protect fossil resources; and (6) contact the NPS Geologic Resources Division for technical assistance with paleontological resource management issues. The NPS Fossils and Paleontology website (http://go.nps.gov/fossils_and_paleo) provides more information

Climate Change Planning and Sea Level Rise

Climate change, in conjunction with other stressors, will probably affect all aspects of park management from natural and cultural resources to park operations and visitor experience (National Park Service 2015a). The park's foundation document noted climate change scenario planning as a data need (National Park Service 2015a). Appendix B of this report lists various laws and policies that provide guidance pertaining to climate change, and the "Additional References" section provides links to websites containing information about climate change, sea level rise, and storm surge.

Increased frequency and severity of wildfires and area burned is a primary threat in the park from climate change (National Park Service 2015a). The park's natural resource condition assessment (Stoms et al. 2013) found that fire frequency could increase dramatically (62%–88%) by the end of the century as a result of climate change. An increase in fire frequency could in turn induce more landslides (see "Landslides" and "Landslide Hazards" sections). Another threat is extreme weather conditions (e.g., drought) resulting from climate change. The outcome of the current drought and widespread dieback of chaparral shrubs in the park is unknown, but loss of vegetation is likely to be a factor for landslides (GRI conference call participants, 17 November 2015).

Climate change will manifest itself as shifts in mean conditions (e.g., increasing mean annual temperature). Stoms et al. (2013) found that climate models consistently projected a 25%–34% increase in "growing degree days" by 2100 at the park scale, resulting in future conditions that are currently found in the western Mojave Desert. Minimum winter temperatures are projected to increase by 2.1°C–2.8°C (3.4°F–4.6°F) while maximum summer temperatures are projected to increase by 4.0°C–5.3°C (6.8°F–9.1°F). Seasonality, measured as the standard deviation of monthly mean temperatures, is projected to increase by 16%–60%. Precipitation projections are variable, either increasing or decreasing, depending on the outcome of a particular global climate model.

Climate change will also manifest itself as changes in climate variability (e.g., more intense storms and droughts). This is a factor for landslides because high levels of precipitation can lead to slope instability and erosional hazards (National Park Service 2015a). Additionally, storm surge height is estimated to increase 0.94 m (3.08 ft) over the next 50 years and 0.96 m (3.14 ft) over the next 100 years (Caffrey 2015), which will impact coastal areas in the park.

Sea level rise is a primary concern with respect to climate change. The park is one of 111 parks that the National Park Service has identified as being vulnerable to sea level rise. Historical sea level trends calculated from the Santa Monica tide gauge (9410840) show that each year between 1933 and 2014, sea level rose 1.5 mm

(0.06 in) (Caffrey 2015). Depending on the emissions scenario, sea level is projected to increase between 14 cm (0.48 ft) and 15 cm (0.49 ft) by 2050, and between 35 cm (1.16 ft) and 49 cm (1.57 ft) by 2100 (Caffrey 2015). In response to sea level rise, property owners are armoring shorelines. This practice is affecting currents and sediment transport and deposition (National Park Service 2015a), which could impact park resources such as beaches.

Peek et al. (2015) determined that no NPS "assets" (e.g., buildings, roads, trails, managed landscapes, or historic structures) in the park are situated on the coast. Thus, all 270 assets have "limited exposure" to 1 meter of sea level rise. During GRI scoping, participants mentioned that private houses along the coast are at risk from sea level rise, in particular the historic Adamson House, which is part of Malibu Lagoon State Beach (a state park) within the national recreation area (fig. 34). With respect to coastal resources, climate change could alter recreational opportunities such as surfing,

Figure 34. Photograph of the Adamson House. No NPS "assets" (infrastructure or historical/cultural resources) are situated on the coast, so none are directly susceptible to 1 meter of sea level rise. However, GRI scoping participants mentioned that private houses along the coast are at risk, in particular the historic Adamson House, which is part of Malibu Lagoon State Beach and within the park's authorized boundary. California Coastal Records Project, Image 200405831, taken 23 October 2004, (http://www.californiacoastline.org/cgi-bin/image.cgi?image=200405831&mode=sequential&flags=0&year=2004). Copyright © 2002-2016 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org.

and ecosystems such as beaches and kelp forests (KellerLynn 2008).

The National Park Service has developed a variety of databases and guidance for managing coastal resources and planning for the impacts of climate change:

- A handbook (Beavers et al. in review) will provide climate change adaptation guidance to park managers in NPS areas vulnerable to sea level change. The handbook will also provide guidance on developing communication and education materials about climate change impacts.
- A report (Schupp et al. 2015) presented 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 Santa Monica Mountains National Recreation Area, but some of the topics (e.g., cultural resource inventory and vulnerability assessments, and developing multiagency vision for an urban coastline) are applicable to resource management at the park.
- Reference manuals that guide coastal resource management include NPS Reference Manual #39-1: ocean and coastal park jurisdiction, which can provide insight for park managers in parks with boundaries that may shift with changing shorelines (http://www.nps.gov/applications/npspolicy/DOrders.cfm); and NPS Reference Manual #39-2: beach nourishment guidance for planning and managing nourishment projects (https://irma.nps.gov/App/Reference/Profile/2185115).
- A cultural resources climate change response strategy, which is under development, will connect climate science with historic preservation planning. The summary report from the 2014 "Preserving Coastal Heritage" workshop identified and described six climate change adaptation options for cultural resources and cultural landscapes: (1) no active intervention, (2) offset stressors, (3) improve resilience, (4) manage change, (5) relocate or facilitate movement, and (6) document and release. Additional information about the workshop, and associated presentations and reports, are available at https://sites.google.com/site/democlimcult/.
- The NPS Geologic Resources Division and NPS Climate Change Response Program are developing sea level rise and storm surge data that park managers can use for planning purposes over

multiple time horizons. The project is scheduled for completion in 2016 and will analyze rates of sea level rise coupled with potential storm surge in 105 of the vulnerable parks in order to project, for each park, the combined elevations of storms surge and sea level by 2030, 2050, and 2100. Numbers from this project (Caffrey 2015) were used in the preceding discussion.

- The NPS Water Resources Division, Ocean and Coastal Resources Branch, website (http://www.nature.nps.gov/water/oceancoastal/) has 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://nature.nps.gov/water/oceancoastal/shorelinemaps.cfm.
- The NPS Geologic Resources Division Coastal Geology website (http://go.nps.gov/grd_coastal) provides information about coastal hazards, climate change, human impacts, and research.

In addition, the California Coastal Sediment Management Workgroup has a website (http://www.dbw.ca.gov/csmw/) that provides links to spatial data, including beach profiles and coastal armoring, which could be incorporated into the park's GIS. Also, historical storm data are stored and maintained as a GIS database by the NPS Geologic Resources Division; original data available at http://www.ncdc.noaa.gov/oa/ibtracs/.

Park managers developing monitoring protocols can contact their NPS Inventory & Monitoring Network coordinator and/or consult suggested protocols such as those in the *Geological Monitoring* chapter by Bush and Young (2009), which described methods for monitoring the following vital signs: (1) shoreline change, (2) coastal dune geomorphology, (3) coastal vegetation cover, (4) topography/elevation, (5) composition of beach material, (6) wetland position/acreage, and (7) coastal wetland accretion.

Earthquakes

Earthquakes are ground vibrations that occur when rocks suddenly move along a fault, releasing accumulated energy (Braile 2009; see "Faults" and "Transform Boundary" sections). The magnitude of an earthquake represents the amount of energy released. The scale measuring the magnitude of an earthquake (i.e., Richter scale) is logarithmic. Thus the magnitude-6.7 Northridge earthquake released 126 times more energy than the magnitude-5.3 Mugu Point earthquake; these earthquakes are discussed below. The US Geological Survey provides a calculator for earthquake magnitude at http://earthquake.usgs.gov/learn/topics/calculator.php.

According to USGS earthquake probability mapping (http://geohazards.usgs.gov/eqprob/2009/index.php), a magnitude 5.3 earthquake has a 0.8 to 0.9 probability (80%–90% "chance") of occurring within 50 km (30 mi) of the Thousand Oaks' zip code (91360) in the next 50 years. A magnitude 6.7 earthquake has a 0.40–0.50 probability (40%–50% "chance") of occurring. This range of earthquake magnitudes (i.e., 5.3–6.7) falls within the range suggested by scoping participants to affect the park (KellerLynn 2008).

Hazards associated with earthquakes at the park include shaking, liquefaction and landslides, tsunami, and seiche. Each of these is described in sections below.

The Malibu Coast and Anacapa-Dume faults are the primary active faults in the Santa Monica Mountains (fig. 10; Pam Irvine, California Geological Survey, senior engineering geologist, email communication, 15 June 2016). The Malibu Coast Fault was the source of the magnitude-5.3 Point Mugu earthquake in 1973, discussed below (California Division of Mines and Geology 1973). The Anacapa-Dume Fault is assumed responsible for generating the historic 1930 Santa Monica earthquake (magnitude 5.2) and the 1979 and 1989 Malibu earthquakes, each of which were magnitude 5.0 (Ziony and Yerkes 1985; Hauksson 1990).

The east-trending Malibu Coast Fault bounds the Santa Monica Mountains on the south. It is a reverse fault with left-lateral movement. The fault is 34 km (21 mi) long and has several parallel strands that run near the communities of Malibu and Pacific Palisades (Southern California Earthquake Data Center 2016). The length of a fault is significant because the longer the fault, the larger the potential earthquake can be (Wells and Coppersmith 1994). The Malibu Coast Fault has a known slip rate of approximately 0.3 mm (0.01 in) per year. The slip rate may be higher at its eastern end, where it meets the Santa Monica Fault (east of the park) (Southern California Earthquake Data Center 2016).

Originally recognized on the basis of bathymetric contours in Santa Monica Bay, the Anacapa-Dume Fault is a near-vertical offshore escarpment exceeding 600 m (2,000 ft) locally, with a total length of 105 km (62 mi) (Yerkes and Wentworth 1965; Junger and Wagner 1977). The fault occurs as close as 5.8 km (3.6 mi) offshore south of Malibu at its western end, but trends northeast where it apparently merges with the offshore segment(s) of the Santa Monica Fault, thus lying as close as 3 km (2 mi) south of the Malibu Beach/Carbon Beach area. Because the Anacapa-Dume Fault appears to truncate the northwest-striking, strike-slip Palos Verdes fault zone of Peninsular Ranges affinity, the Anacapa-Dume Fault is considered the present-day southern margin of the zone of thrust faults that punctuate the Transverse Ranges province (General Plan Task Force 2016). The Anacapa-Dume Fault has a known slip rate of approximately 0.3 mm (0.01 in) per year (Jennings and Bryant 2010).

The Hollywood Fault and the Santa Monica Fault, which are at or close to the base of the Santa Monica Mountains, also are potential sources of earthquakes that would affect the eastern Santa Monica Mountains (Pam Irvine, California Geological Survey, senior engineering geologist, email communication, 15 June 2016). Both of these faults are reverse faults with left-lateral movement. The Hollywood Fault has the potential to produce an earthquake between magnitude 5.8 and 6.5; liquefaction and earthquake-induced landslides are hazards (California Geological Survey 2014). The Santa Monica Fault has a probable magnitude of 6.0–7.0 (Southern California Earthquake Data Center 2016). The California Geological Survey produced an earthquake planning scenario/shakemap for the Santa Monica Fault and other faults in the Santa Monica Mountains (see "Additional References" section).

Point Mugu and Northridge Earthquakes

The effects of past earthquakes can provide an understanding of what to expect from a future earthquake. The Point Mugu earthquake, which shook the Santa Monica Mountains on 21 February 1973, was the third-strongest US earthquake and the strongest in the contiguous 48 states that year. It was responsible for at least five injuries and more than $1 million damage in the Point Mugu–Oxnard area, though damage was mainly confined to the epicentral area. Large boulders fell onto Highway 1 at Point Mugu, partially blocking the road. More than 7,000 customers were without electricity for hours. Most damage reported was to windows, ceilings, plaster, chimneys, and shelved goods, though structural damage and broken pipes were also reported (Southern California Earthquake Data Center 2016).

Another earthquake of interest for the Santa Monica Mountains is the 1994 Northridge earthquake, which occurred on 17 January 1994 on the Northridge Thrust (a thrust fault also known as the Pico Thrust). The fault is north of the park about 30 km (20 mi) west–northwest of Los Angeles and/or 2 km (1 mi) south–southwest of Northridge. The earthquake produced the strongest ground motions ever instrumentally recorded in an urban setting in North America. Damage was widespread; sections of major freeways collapsed, parking structures and office buildings collapsed, and numerous apartment buildings suffered irreparable damage. Damage to wood-frame buildings, especially apartments, was very widespread in the San Fernando Valley and Santa Monica areas. The high accelerations, both vertical and horizontal, lifted structures off of their foundations and/or shifted walls laterally. The earthquake revealed that the systems of concealed faults under the Los Angeles area are more complex than previously thought (Southern California Earthquake Data Center 2016).

Shaking

The primary hazard associated with earthquakes in the Santa Monica Mountains area is shaking produced by the sudden rupture of a fault. It is these ground motions that are felt and that cause most of the damage. Although an earthquake has only one magnitude and epicenter, different locations will experience different shaking levels. The strongest shaking occurs very near the fault and dies off as seismic waves travel away. Away from the fault, natural basins filled with sediments trap some 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 the Northridge and other earthquakes (see "Additional References" section).

Liquefaction and Landslides

Large earthquakes in southern California can trigger liquefaction (a phenomenon in which the strength

Figure 35. Photograph of the Pacific Palisades. The sedimentary rocks of the Pacific Palisades area (Qtms) are susceptible to slumping, which may be triggered by earthquake shaking. The bluffs occur along the Pacific Coast Highway. Photograph by Katie KellerLynn (Colorado State University).

and stiffness of sediment or soil is reduced by earthquake shaking) and landslides (see "Landslides" and "Landslide Hazards" sections). Conditions for liquefaction, that is loosely packed, water-logged sediments at or near the ground surface, commonly occur in coastal areas, at the mouths of rivers, and in artificial fill (**Qaf**). With respect to the park, the Santa Clara River/Oxnard Plain areas of Ventura County and portions of the coastal basin or flatland areas of Los Angeles County are susceptible to liquefaction.

Shaking in the Santa Monica Mountains area has the potential to generate thousands of individual landslides (Jones et al. 2008). The most common manifestation of the Northridge earthquake in the Santa Monica Mountains was the rockfalls and rockslides that fell onto roads from the platy shale layers of the Modelo Formation ("**Tm**" map units) exposed in deep cuts (Barrows et al. 1995). Also, bluff failure is likely in the Pacific Palisades area and Santa Monica Canyon (Pam Irvine, California Geological Survey, senior engineering geologist, telephone communication, 9 June 2016). During the Northridge earthquake, the Pacific Palisades experienced locally spectacular bluff failures along the Pacific Coast Highway (fig. 35). The collapse of bluffs damaged or destroyed several homes and caused the closure of the highway between Chautauqua Boulevard and Temescal Canyon Road for several days. Ongoing failures are likely following a large earthquake, perhaps during the next rainy season, where brittle bluff-top terrace deposits, which are very susceptible to slumping, developed cracks from the strong shaking (Barrows et al. 1995).

The California Geological Survey provides liquefaction and landslide hazard zone maps for all of the quadrangles (scale 1:24,000) covering the park and surrounding areas (see "Additional References" section).

Tsunami

Scoping participants concluded that tsunamis (earthquake-generated waves) are not a significant hazard in the park because much of the park's coastline is protected by the Channel Islands and the offshore shelf and slope. Nevertheless, scoping participants thought large, submarine landslides had the potential to cause local-scale tsunami. For example, large submarine slides have occurred in the Santa Barbara Basin and off the northwestern edge of the San Pedro shelf (into the Santa Monica Basin) (Chris Wills, California Geological Survey, geologist, email communication, 16 September 2008). Flooding and wave activity would be expected. The most vulnerable objects would be people on the beaches, houses or other buildings constructed on or near the beach, and bridges over the streams near the beach, such as along the Pacific Coast Highway at Malibu Creek and Corral Creek. People could be swept away by the waves and drowned; buildings and bridges could be undermined and collapse or carried away by the currents; buildings and other structures could be battered by debris carried by the currents (General Plan Task Force 2016).

The California Geological Survey has completed tsunami inundation maps for the entire coastline in the park (see "Additional References" section). NOAA provides tsunami information and warnings for the entire Pacific Rim area, including the west coast of the continental United States, Alaska, and Hawaii (see "Additional References" section).

Seiche

Seiche (standing waves in an enclosed or partially enclosed body of water such as Santa Monica Bay) may be triggered by local submarine earthquakes, and sometimes by large, more distant, regional earthquakes. This phenomenon was recorded at Santa Monica following moderate (magnitude 5.0–5.2) earthquakes under Santa Monica Bay in 1930, 1979, and 1989. The maximum height of these long period waves was about 0.6 m (2 ft). If such oscillations occurred during storm conditions or unusually high tides, damaging coastal inundation could result. The duration of these oscillations may be several hours (General Plan Task Force 2016).

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 risk analysis specific to the park has not been conducted, but park managers are encouraged to contact the NPS Geologic Resources Division with questions about earthquake risk. GRD staff can conduct risk assessment of unstable slopes that could be triggered to fail during an earthquake.

Detailed information about earthquake risk is provided by scenarios, such as the HAZUS scenario and annualized earthquake loss estimation for California (Chen et al. 2011) and the ShakeOut Scenario (Jones et al. 2008). Scenarios estimate the scale and extent of damage, social disruption, and economic losses due to potential earthquakes. In addition, many organizations provide information about risk and preparedness that would be useful for park planning (see "Additional References" section).

Cave and Karst Resource Management

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) the 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).

The "Cave and Karst Resources" section of this report describes the known cave and karst resources in the park, and Soto (2013) completed a cave and karst resource summary. However, the park is in need of a comprehensive cave inventory (KellerLynn 2008; National Park Service 2013; Soto 2013). The NPS Geologic Resources Division could assist park managers in initiating an inventory, which should include physical maps and an inventory of features and animal use (Dale Pate, NPS Geologic Resources Division, National Cave and Karst Program Manager, written communication, 10 December 2015). Following an inventory, the NPS Geologic Resources Division could assist park managers in developing a cave management plan, as needed. Such plans include a comprehensive evaluation of current and potential visitor use and activities, as well as a plan to study known and discover new caves. The NPS Cave and Karst Resources website (http://go.nps.gov/cavesandkarst) provides more information.

Some of the following vital signs, described by Toomey (2009) in *Geological Monitoring*, may be of interest and use to park managers in developing a monitoring plan: (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.

The following connections exist between cave/karst resources and other resources in the park:

- Paleontological. The park contains fossiliferous limestone, which is both a cave/karst resource and a paleontological resource. Limestone occurs as part of the Fernwood Member (**Ttcf**) of the highly fossiliferous Topanga Canyon Formation and in the Santa Susana Formation (**Tss** and **Tssl**) (see "Paleontological Resources" section).
- Biological. A study by Brown and Berry (2005) identified the presence of 11 bat species in the park. Whether bats are using the caves as habitat is unclear, however (National Park Service 2013). The caves at the park might host endemic and endangered species that need to be documented or protected. Park managers are encouraged to contact the NPS Biological Resources Division (http://nature.nps.gov/biology) for more information. White-nose syndrome (WNS) is a fungus that is killing bats in the eastern and central United States, and was recently detected in the West Coast (Cornwall 2016).
- Hydrological. Human consumption and disposal of water affects local and regional hydrologic systems, including groundwater discharge and underground streams, which can impact cave and karst systems. Monitoring water resources at the park is a need because urban development threatens hydrological resources and potentially cave and karst resources. Park managers are encouraged to contact the NPS Water Resources Division (http://nature.nps.gov/water) for more information about water quality and quantity.

Flooding and Dam Failure

During the winter rainy season, streams may overtop their channels and overflow their banks, flooding park infrastructure. During such events, parking lots have washed out. Also, floodwaters threaten cultural resources at Peter Strauss Ranch (KellerLynn 2008).

Twenty eight "water" polygons, including lakes and reservoirs, are part of the GRI GIS data. Most of the small water bodies in the park are stock ponds that were used for past ranching (GRI conference call participants, 17 November 2015). As part of a national wetlands inventory, park staff documented all known vernal ponds in the park (KellerLynn 2008). Most natural ponds in the park have been dammed to increase their areas, and an outcome is the potential for dam failure and damage to downstream cultural resources. Park managers are considering whether to maintain these small reservoirs or restore the ponds to natural conditions (KellerLynn 2008). The estimated 10 largest water bodies within the park are reservoirs and do not belong to the National Park Service. The primary concern with these reservoirs is dam failure and damage to homes below (KellerLynn 2008).

Malibu Creek and the stream running through Solstice Canyon have been dammed. Excessive sedimentation is a management issue in these areas.

A variety of publications and resources provide park-specific or servicewide information and management guidance about upland and fluvial processes (see "Additional References" section and Appendix B of this report). Park managers are encouraged to contact the NPS Geologic Resources Division for technical assistance.

Abandoned Mineral Lands and Other Disturbed Lands

Abandoned mineral lands (AML) are lands, waters, and surrounding watersheds that contain facilities, structures, improvements, and disturbances associated with past mineral exploration, extraction, processing, and transportation, including oil and gas features and operations, for which the National Park Service takes action under various authorities to mitigate, reclaim, or restore in order to reduce hazards and impacts to resources.

The NPS AML database and Burghardt et al. (2014) list no AML features or sites within the park. Park managers are encouraged to contact the NPS Geologic Resources Division with information about (see discussion below) or assistance with any AML features or sites. All AML features and sites should be inventoried and documented in the servicewide database.

Compared to other mountain ranges in the Transverse Ranges, very little historic prospecting occurred in the Santa Monica Mountains. Nevertheless, mineral exploration resulted in a few limestone quarries in the Santa Ynez Canyon area (KellerLynn 2008). Notably, an adjoining canyon to Santa Ynez Canyon is named "Quarry Canyon," which is within the park's authorized boundary in Topanga State Park. Quarry Canyon incised into the Santa Susana Formation (**Tss**), which contains lenses and pods of algal limestone (see "Cave and Karst Resource Management" section), and Sespe Formation (**Ts**). Scarred limestone, as well as sandstone, cliffs along Quarry Canyon give testament to once-extensive, and controversial, early to mid-20th century extractive industries associated with noted real estate developer Alphonzo Bell (California Department of Parks and Recreation 2009). The topographic map of the area shows one quarry in the Santa Susana Formation (**Tssl**) in the vicinity of Santa Ynez Canyon but outside the park.

Oil and gas exploration and development produced some dry holes on Point Dume. Point Dume is within the authorized boundary of the park but not currently administered by the National Park Service.

Oil and gas production took place on lands within the Santa Susana Mountains north of the park. The National Park Service is currently conducting a resource study of lands that have the potential to be acquired. Some of these properties in the Santa Susana Mountains may include disturbed lands (Denise Kamradt, Santa Monica Mountains National Recreation Area, GIS specialist, conference call, 17 November 2015). Park managers are encouraged to contact the NPS Geologic Resources Division for assistance with disturbed lands restoration (see http://go.nps.gov/grd_dlr). Usually, lands disturbed by natural phenomena such as landslides, earthquakes, floods, and fires are not considered for restoration unless influenced by human activities. Restoration activities return a site, watershed, or landscape to some previous condition, commonly some desirable historic baseline.

Geologic History

This section describes the chronology of geologic events that formed the present landscape of Santa Monica Mountains National Recreation Area.

This summary of the park's geologic history follows Fritsche and Weigand (2008), which served as a handout during the 2008 GRI scoping meeting. Table 1 presents a tabular version of the geologic history described in this section, including a chronology and brief descriptions of map units, depositional settings, colors representing major tectonic regimes, and locations of unconformities.

Notably, the nature and timing of some of these geologic events remains controversial and different models proposed over the years continue to evolve as new information becomes available. Sources of information that helped to inform this section include Crouch and Suppe (1993), Nicholson et al. (1994), Atwater (1998), Ingersoll and Rumelhart (1999), and Olson (2006). The timing of events in those sources may vary from Fritsche and Weigand (2008).

Southern California was once the site of a convergent boundary, where the Farallon plate subducted beneath the North American plate. As Farallon plate subduction progressed, the northern end of a divergent boundary—the East Pacific Rise—made contact with the subduction zone. Through a process of microplate capture and stalling of plate subduction, the convergent boundary evolved into a transform boundary, where the Pacific and North American plates slide horizontally past each other. However, the new plate boundary in southern California was never a pure transform boundary but included an extensional component ("transtension") then a compressional component ("transpression"). Transtension was responsible for reconfiguration of the continental rim, including rotation of the Western Transverse Ranges block, eruption of the Conejo Volcanics, and deposition of sediments in extensional marine basins. After Baja California was captured by the Pacific plate, transtension changed to transpression, which continues to cause folding, uplift, tilting, and faulting in the Santa Monica Mountains.

Subduction

As dinosaurs walked the Earth in the Jurassic and Cretaceous periods (fig. 13), two tectonic plates—one oceanic, the Farallon, and one continental, the North American—converged off the western edge of the continent. A subduction zone was created where the thinner, denser Farallon plate descended beneath the thicker, more buoyant North American plate (fig. 4). In California, the convergent margin, which existed from the Mesozoic Era through the early Cenozoic Era (Paleogene Period), is characterized by four belts or assemblages of rocks aligned subparallel to the generally northwest–trending continental margin (see "Convergent Boundary" section). Figure 4 shows a cross section of this continental-margin subduction system, as well as four the lithotectonic belts, their inferred tectonic settings, and the associated correlations with rocks in the Santa Monica Mountains and surrounding area.

Three of these belts are recognized in the rocks of the park. First, the "accreted arcs" belt is represented by the Santa Monica Slate ("**Jsm**" units; table 1). Sediments that were later metamorphosed to become slate were deposited between 156 million and 152 million years ago in an ocean basin that may have been associated with an island arc system adjacent to the continental-margin subduction zone. The island arc terrane was later accreted to the continent during the Late Jurassic–Early Cretaceous (?) periods (Crouch and Suppe 1993; Schweickert 2015). Second, about 102 million years ago (Cretaceous Period), melting of the subducting Farallon plate produced plutons (bodies of rock formed by an igneous intrusion) that intruded the Santa Monica Slate; granitic rocks (**Kgr**) in the park represent these plutons. These rocks are part of the "magmatic arc" belt (fig. 4) and are associated with the granitic rocks in the Peninsular Ranges south of the park and the Sierra Nevada north of the park. Third, the "forearc basin" belt is represented by a sequence of Upper Cretaceous–Oligocene sedimentary rocks in the park (discussed below).

Folding of the Santa Monica Slate, perhaps as a result of compression related to the subduction of the Farallon plate, produced a generally north–south-trending anticline. As the slate and granitic plutons were uplifted as part of the anticline, all overlying rocks were eroded away, creating an unconformity (a nonconformity) and leaving the Santa Monica Slate and granitic rocks exposed at the surface. The nonconformity separates the metamorphic Santa Monica Slate ("**Jsm**" map units) and intruded igneous granitic rocks (**Kgr**) from overlying sedimentary rocks. It is the oldest unconformity recorded in the park's rock record and formed 102 million–91 million years ago (Cretaceous Period).

While the nonconformity developed, deep erosion also produced a west-trending, subaerial canyon. Evidence of this canyon occurs near Tarzana, California, so it is referred to as "Tarzana Canyon" (Eugene Fritsche, California State University, Northridge, Department of Geological Sciences, professor emeritus, GRI scoping presentation, 7 May 2008). The canyon had a minimum depth of 400 m (1,300 ft) as indicated by the thickness of alluvial-fan and river deposits of the Trabuco Formation (**Ktr**), which filled it. Trabuco Formation sediments were deposited about 91 million–90 million years ago (Late Cretaceous Period) (fig. 36).

Atop the Trabuco Formation, the sedimentary succession of forearc-basin rocks related to the Great Valley belt is recorded by the Tuna Canyon Formation (**Kt**) and its informal members (**Ktb**, **Kte**, **Ktd**, **Ktc**, and **Ktb**) as well as the Chatsworth Formation (**Kc**). These sediments were deposited between 90 million and 75 million years ago in fan-delta and submarine-fan environments (fig. 37).

As subduction continued between 75 million and 58 million years ago (Late Cretaceous Period–late Paleocene Epoch), existing rocks were uplifted and deformed. Erosion accompanied uplift and produced a second unconformity (an angular unconformity) upon which a subdued, subaerial Tarzana Canyon was reestablished. This unconformity is called the Runyon Canyon erosion surface, which is a regionally significant feature that also marks the K-T boundary, more formally known as the Cretaceous-Paleogene (K-Pg) boundary (see "Unconformities" section).

The distinctive Paleocene to Eocene sedimentary sequence that was deposited on the Runyon Canyon erosion surface includes the Simi Conglomerate (**Tsi**), the Las Virgenes Sandstone (**Tlv**), and Santa Susana Formation (**Tss** and **Tssl**) (Colburn and Novak 1989). These rocks represent a marine transgression (see "Transgressive–Regressive Cycles" section) that took place about 58 million–55 million years ago.

Figure 36. Photograph of the Trabuco Formation. Between 91 million and 90 million years ago, alluvial fans and streams deposited sand, gravel, cobbles, and boulders that now compose the Trabuco Formation, which filled "Tarzana Canyon." The exposure shown here is in a canyon just north of Mulholland Drive. The large size of the boulders suggests a powerful mountain stream. Rock hammer (total length approximately 28 cm [11 in]) for scale. Photograph from Eugene Fritsche (California State University, Northridge, Department of Geological Sciences, professor emeritus, GRI scoping presentation, 7 May 2008).

Figure 37. Photograph of the Tuna Canyon Formation. This photograph taken at an exposure along Mullholland Drive shows a close-up view of the sandstone portion of the Tuna Canyon Formation. The Tuna Canyon Formation was deposited in fan-delta and shallow- to deep-marine submarine-fan environments. Rock hammer (total length approximately 28 cm [11 in]) for scale. Photograph from Eugene Fritsche (California State University, Northridge, Department of Geological Sciences, professor emeritus, GRI scoping presentation, 7 May 2008).

Figure 38. Photograph of the angular unconformity between the Llajas and Santa Susana formations. When southern California was mildly uplifted between 55 million and 50 million years ago, the area was eroded, and a third unconformity surface formed. The exposure shown in the figure is on Rambla Pacifico Road just north of its intersection with Las Flores Canyon Road. The orange line on the photograph marks the unconformity. Photograph by Pam Irvine (California Geological Survey).

Uplift, erosion, and renewed mild deformation along the previous anticlinal trace produced a third and fourth unconformities (angular unconformities) at about 55 million–50 million years ago and 48 million–41 million years ago (Eocene Epoch). These unconformities bracket the Llajas Formation (**Tl**) in the rock record at the park (fig. 38). The Llajas Formation, which consists of a nonmarine alluvial to shallow-marine basal conglomerate and overlying shallow-marine to offshore shelf deposits of sandstone and siltstone, was deposited during a marine transgression about 50 million–48 million years ago (Eocene Epoch).

The fifth unconformity (a disconformity) in the park's rock record occurs in the middle of the lower Sespe Formation (**Ts**). It developed about 36 million–29 million years ago as the approach of the East Pacific Rise caused regional uplift of the North American continental margin (see "Divergent Boundary" section). Deposition of the Sespe (**Ts**) nonmarine fluvial and deltaic sediments resumed between 29 million and 28 million years ago. These sediments record the final stages of subduction-related deposition.

Transition from Subduction to Transform Plate Motion

The uppermost part of the Sespe Formation—the Piuma Member (**Tsp**)—and the overlying Vaqueros Formation ("**Tv**" map units) were probably deposited in an extensional basin that formed at the site of the former forearc basin between 28 million and 21 million years ago (Fritsche 1998; Fritsche and Weigand 2008). Between 21 million and 18 million years ago, the Topanga Canyon Formation ("**Ttc**" map units) was deposited atop the Vaqueros Formation during two transgressive–regressive cycles. The Topanga Canyon Formation consists of both nonmarine and marine sediments that originated in fluvial, marine delta, and continental-shelf settings.

The Piuma Member of the Sespe Formation, the Vaqueros Formation, and the early Miocene part of the Topanga Canyon Formation were deposited during the transition from subduction to transform plate motion. At 28 million years ago, the East Pacific Rise encountered the western margin of North America. As the spreading center approached the subduction zone, the Farallon plate east of the rise began to fracture into microplates. The fragment of the Farallon plate in the vicinity of the future Transverse Ranges is referred to as the "Monterey microplate" (Atwater 1970). This fragment of the Farallon plate continued to be subducted, but at a much slower rate than adjacent microplates. This was due to a dramatic decrease in spreading at the then Pacific plate–Monterey microplate boundary; divergent motion ceased about 20 million years ago, prior to complete subduction of the Monterey microplate (Nicholson et al. 1994). When spreading ceased between the Pacific plate and Monterey microplate, the microplate was in a sense "captured" by, or locked onto, the Pacific plate. This event is important because the Monterey microplate, which was previously being subducted obliquely to the northeast, began to assume Pacific–plate relative motion that was more northwesterly (Nicholson et al. 1994; Atwater and Stock 1998). This change signified the beginning of transform plate motion in proto–southern California (Olson 2006).

Transtension

The transform boundary in southern California was initially characterized by transtension (transform plate motion and extension). At least three significant, interrelated events accompanied transtension between

20 million and 4 million years ago: (1) rifting and rotation of the Western Transverse Ranges block, (2) volcanism, and (3) sediment deposition in extensional basins.

Rotation

Transtension coupled with irregularities in the geometry of the plate boundary led to deformation of the continental crust and formation of three large, fault-bounded blocks (Atwater 1998). As plate motion changed from convergent to transform, the basal shear generated by the underlying Monterey microplate separated these north–south-oriented blocks from North America (fig. 7). The outer two blocks became attached to the Pacific plate and have been transported up the coast and slightly seaward ever since (Atwater 1998). The third block, the Western Transverse Ranges block, which was farther inland than the other two, was trapped at its northern end against the North America plate by a bend in the plate boundary and, as a consequence, began to rotate clockwise, inserting its southern end between the other two blocks. Rotation of the Western Transverse Ranges block explains why today's Transverse Ranges run east–west in contrast to the northwest–southeast orientation of most other mountain ranges in California (see "Transform Boundary" section).

Figure 39. Photograph of the Conejo Volcanics on the landscape. Boney Mountain and other peaks along the Backbone Trail are composed of Conejo Volcanics ("Tco" map units). National Park Service photograph.

Rotation continues to the present day, though interpretations vary. For example, Luyendyk (1991) preferred to interpret the available paleomagnetic data as indicating a constant rotation rate from 18 million years ago to the present. Ingersoll and Rumelhart (1999), by contrast, interpreted these data as indicating rapid rotation of the entire block from 18 million to 12 million years ago, with complex local rotations thereafter.

Between 18 million and 17 million years ago, crustal extension, deformation, and erosion resulting from rifting and rotation of the Western Transverse Ranges block created an angular unconformity that was covered by volcanic rocks (see "Volcanism" section below). This is the sixth unconformity in the park's rock record and is evidence that significant tectonic deformation was occurring prior to the onset of volcanism in the Santa Monica Mountains.

Volcanism

As rifting, rotation, and crustal extension continued, Earth's stretching and thinning crust allowed magma to intrude the overlying crustal rocks and erupt at the surface, producing a period of volcanism in the Santa Monica Mountains area. Most of the volcanism took place near the site of rifting between the Western Transverse Ranges block and Peninsular Ranges at what is now the southern edge of the rotated Western Transverse Ranges. Intrusive and extrusive volcanic rocks (**Ttb**), which are exposed in the eastern Santa Monica Mountains, represent the onset of volcanism. Mixed rocks (**Tim**) and intrusive rocks (**Ti**, **Tid**, **Tia**, and **Tib**), which intruded the preexisting Topanga Canyon Formation, also represent this period of volcanism. The mixed and intrusive rocks in the central and western Santa Monica Mountains are associated with the Conejo Volcanics ("**Tco**" map units; fig. 39), which erupted and accumulated at the bottom of the ocean. Conejo Volcanics formed a volcanic complex that included shield volcanoes that rose above sea level. The Conejo volcanic complex represents one of the largest middle Miocene accumulations of intrusive and extrusive rocks in southern California (see "Igneous Rocks" section).

Extensional Basins

As a result of ongoing crustal extension in proto–southern California during the Miocene Epoch, older basins were significantly modified and several separate sub-basins or depositional centers were formed. Basin development is related to microplate-capture events along the continental margin (Ingersoll and Rumelhart 1999). These incipient basins, which heralded the beginnings of the Los Angeles Basin, accommodated sediment influx during two different phases of basin development in the middle Miocene Period and middle-to-late Miocene Period (Ingersoll and Rumelhart 1999).

In the Santa Monica Mountains, middle Miocene sedimentary and volcanic (see "Volcanism") rocks of the Topanga Group were deposited in extensional basins during a period of rapid subsidence from about 18 million to 12 million years ago resulting from Monterey microplate capture and onset of rifting, extension, and rotation (Ingersoll and Rumelhart 1999). The Calabasas Formation ("**Tcb**" map units), the youngest formation of the Topanga Group, consists of deep-water sandstone and shale beds that intertongue with and overlie the Conejo Volcanics. They were deposited by offshore marine turbidity (sediment-laden density) currents while the Conejo Volcanics were erupting from nearby volcanoes.

Continued rotation, deformation, uplift, and erosion created an angular unconformity about 13 million–12 million years ago (Miocene Epoch). This is the seventh unconformity preserved in the Santa Monica Mountains area; it occurs at the base of the Modelo Formation in the park's rock record. This unconformity may be related to the Pacific plate capture of the remaining pieces of the Farallon plate, which were being subducted beneath Baja California between 14 million and 12 million years ago.

That plate-capture event and the subsequent change in plate boundary configuration may have also initiated the formation of the basins into which sediments of the Modelo Formation ("**Tm**" map units) were deposited (Ingersoll and Rumelhart 1999) between 12 million and 4 million years ago (Fritsche and Weigand 2008). The Modelo Formation was deposited as deep-water submarine fans (sandstone) interbedded with finer grained sediments. It represents submergence and a transgression in rapidly subsiding transtensional basins.

Rock Sequence South of the Malibu Coast Fault

The rocks exposed south of the Malibu Coast Fault (table 1b) in the central and western Santa Monica Mountains consist of the Zuma Volcanics (**Tz**; basaltic submarine volcanic rocks), Trancas Formation (**Tr** and **Tra**; marine mudstone, sandstone, and conglomerate), and Monterey Shale (**Tmt** and **Tmtd**; calcareous and dolomitic shale). These overlapping units split into many thin tongues and pinch out and disappear laterally east and west (fig. 40). These strata are generally coeval with the Topanga Group and Modelo Formation north of the fault (see "Formations" section and table 1a).

The Trancas Formation contains lenses of a locally prominent sedimentary breccia—the San Onofre Breccia (fig. 41)—which is composed almost entirely of angular clasts of Early Cretaceous Catalina Schist (part of the Franciscan Subduction Complex or "accretionary wedge" belt; fig. 4). In the park area, the San Onofre Breccia in the Trancas Formation crops out along the beach at Lechuza Point and at Point Dume. The occurrence and distribution of this distinctive breccia provides important clues to understanding the early to middle Miocene tectonic evolution of the plate boundary in southern California, in particular rotation of the Western Transverse Ranges block and the opening of the proto–Los Angeles Basin to the east.

In the central Santa Monica Mountains, the sequence of rocks south of the Malibu Coast Fault differs from the rocks north of the fault because it (1) is missing the Late Cretaceous to Paleogene forearc basin strata, (2) commonly contains lenses of San Onofre Breccia, and (3) is inferred to have been deposited on Catalina Schist basement rocks. The rock sequence south of the Malibu Coast Fault is more similar to the section of rocks on the Palos Verdes Peninsula (south of the park) and strata in the inner-continental borderland (offshore southern California). The rocks south of the Malibu Coast Fault were deposited in extensional basins in an area in the inner-continental borderland where the gap that formed in the wake of the rotating Western Transverse Ranges block had widened enough to expose the underlying metamorphosed mid-crustal basement rock (i.e., Catalina Schist), which was uplifted, eroded, and incorporated as clasts into the San Onofre Breccia. Extension and crustal thinning at that time also allowed for the upwelling of mantle material and the formation of magma that intruded the overlying rocks and erupted into marine basins as sediments were being deposited on an irregular surface of Catalina Schist.

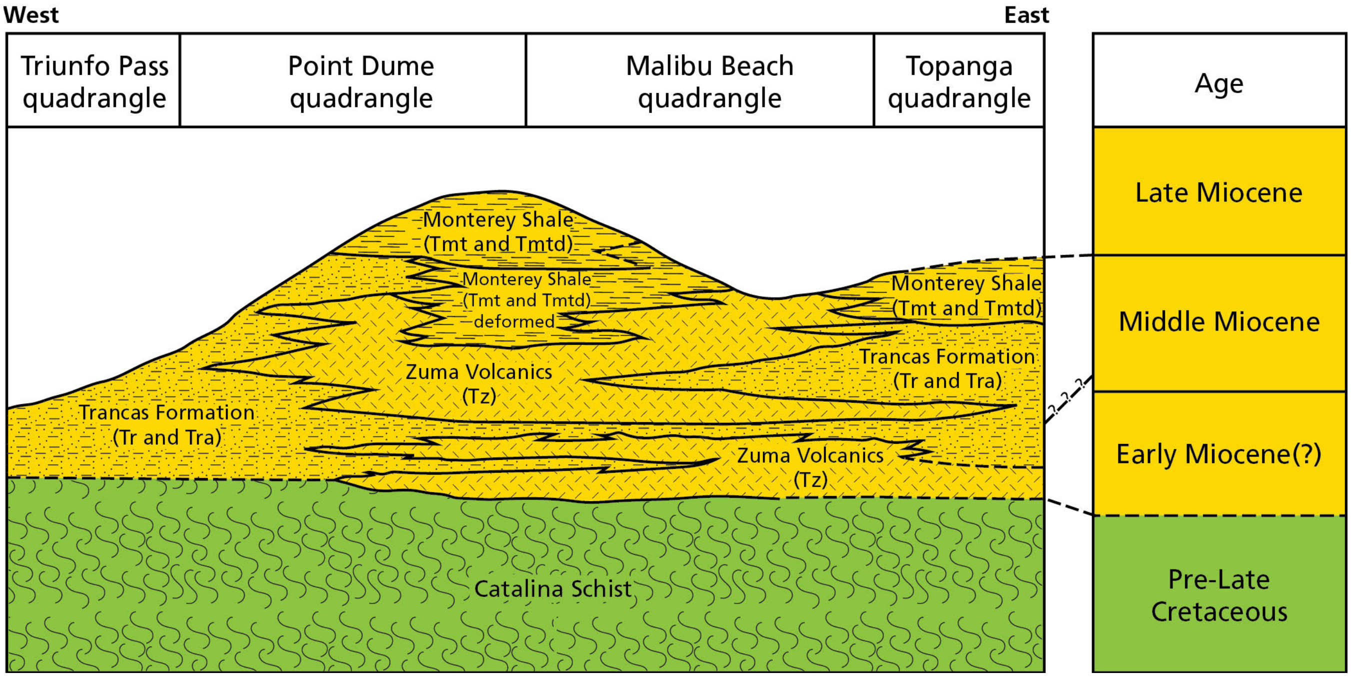

Figure 40. Correlation diagram of rocks south of the Malibu Coast Fault. The Zuma Volcanics (Tz), Trancas Formation (Tr and Tra), and Monterey Shale (Tmt and Tmtd) intertongue and pinch out laterally east and west in the central and western Santa Monica Mountains. Deposition took place in an extensional basin during much of the Miocene Epoch. The Zuma Volcanics erupted during the early and middle Miocene Epoch in an expanding submarine basin. The Trancas Formation was deposited during the early and middle Miocene Epoch as mud, sand, and gravel entered the basin. The Monterey Shale formed during the early, middle, and late Miocene Epoch as silt settled into a deep marine basin. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Yerkes and Campbell (1979, figure 5).

Transpression

Approximately 4 million years ago (Pliocene Epoch), the tectonic regime of southern California completely changed when the Pacific plate captured Baja California and began transporting it northwestward, ramming its northern end into southern California. Another way to describe this event is that the southern section of the Pacific–North America plate boundary shifted from the Pacific coast into the Gulf of California and the plate boundary had to break a new path across southern California, reconfiguring itself to connect to this new inland plate boundary. The transtensional system was largely deactivated at this time, and the southern California segments of the San Andreas Fault system were formed (Atwater 1998).

The pressure of Baja California pushing northwest against southern California bolstered transpression. In this new configuration, the Western Transverse Ranges block is snagged at its (now) eastern end, against the "Big Bend" in the San Andreas Fault (fig. 7). As a result, the block is moving westward around the bend and shortening north–south. Compression associated with the bend is forcing up the land along preexisting structures (faults and folds), raising the Santa Monica Mountains. Initiation of mountain building, cessation of deposition of the Modelo Formation ("**Tm**" map units), left-shearing of the entire mountain range, and left-slip faulting on the Benedict Canyon and Malibu Coast faults are geologic evidence of transpression (Fritsche and Weigand 2008).

To accommodate the western motion of the Western Transverse Ranges block around the Big Bend, major left-lateral faults (fig. 9) have formed along the southern edge of the block, and many preexisting Miocene normal faults (associated with extension) have been inverted into reverse faults (associated with transform plate motion) (Atwater 1998). At the southern edge of the Transverse Ranges, faulting is causing the uplift of the Santa Monica Mountains and the Channel Islands. Numerous young folds and uplifted, tilted marine terraces on the Channel Islands are evidence of ongoing shortening and uplift (Sorlien and Pinter 1997; Sorlien et al. 1998). In addition, crustal shortening—related to movement along blind thrust faults, in the subsurface

Figure 41. Photographs of San Onofre Breccia. The Trancas Formation contains distinctive beds of San Onofre Breccia, which is composed almost entirely of angular clasts of Early Cretaceous Catalina Schist. The schist is part of the Franciscan Subduction Complex or "accretionary wedge" belt (fig. 4). The breccia represents regional extension where the Catalina Schist basement rocks became exhumed. Photographs by Pam Irvine (California Geological Survey).

of the northern Los Angeles Basin and valleys and hills north of the park—is causing earthquakes, such as the Northridge earthquake (see "Earthquakes" section).

Sedimentary rocks in the park that have been deposited since transpression began are limited to a few exposures of sedimentary rocks of the Pacific Palisades area (**QTms**). This unit consists of locally fossiliferous marine siltstone and sandstone. It also includes a basal sedimentary breccia (landslide?) unit, which probably resulted from submarine slumping on the margin of the basin (McGill 1989).

As shown in the GRI GIS data, Quaternary ("**Q**") units record deposition in primarily terrestrial settings during the last 2.6 million years. Changing sea levels—influenced by tectonic uplift locally and the growth and melting of ice sheets globally—have affected landscape development. Marine terraces document past sea-level highstands. These features were mapped as old shallow marine deposits on wave-cut surface (**Qom**). Quaternary features in the park also include old fan deposits (**Qof1**, **Qof2**, and **Qof4**; late Pleistocene Epoch, 126,000–11,700 years ago) and old alluvium (**Qoa**; middle to late Pleistocene Epoch, 781,000–11,700 years ago). "Old" deposits have been uplifted and are no longer active sites of sedimentation.

Young alluvial-fan deposits (**Qyf** and **Qyf2**) of late Pleistocene and Holocene age (126,000–0 years ago) were deposited chiefly by flooding streams and debris flows and are associated with modern alluvial fans. In addition, streams deposited young alluvium (**Qya**, **Qya1**, and **Qya2**) on canyon floors. Like young alluvial-fan deposits, young alluvium is related to ongoing processes. The most recent (in the last 11,700 years; Holocene Epoch) fluvial activity is recorded by alluvial fans (**Qf**) and alluvium (**Qa**). Also, Holocene wash deposits (**Qw** and **Qw1**) are chiefly stream deposited but include some debris-flow deposits.

Landslides—represented by landslide deposits (**Qls**) as well as hazard point/area features in the GRI GIS data—are a primary feature of the park's landscape (see "Landslides" section). The exact timing of the onset of landsliding is unclear but may have started as much as 126,000 years ago (late Pleistocene

Epoch). Landsliding is ongoing (see “Landslide Hazards” section).

The park also contains modern estuaries, dunes, and beaches. Active coastal estuarine processes transport and deposit submerged/saturated silty clay (**Qes**). The wind creates eolian deposits (**Qe**), primarily transitory dunes against beach-facing cliffs, such as the “Great Dune” (see “Eolian Features and Processes” section). Beach deposits (**Qb**) consist of loose sand from reworked fluvial-deltaic and nearshore deposits.

Archeological evidence indicates that humans arrived in the northern Channel Islands at least 13,000 years ago (Erlandson et al. 2007). Humans have remained on the landscape of southern California since that time. Modern anthropogenic activities include construction, mining, and quarrying as represented by artificial fill (**Qaf**). Artificial fill is composed of sand, silt, and gravel that is commonly compacted and engineered. Only large deposits of artificial fill are shown in the GRI GIS data, but such deposits (mapped at scale 1:24,000) illustrate the ongoing influence of humans on the landscape.

Geologic Map Data

This section summarizes the geologic map data available for Santa Monica Mountains National Recreation Area. A poster (in pocket) displays the geologic map data draped over imagery of the park and surrounding area. Complete GIS data are available at the GRI publications website: http://go.nps.gov/gripubs.

Geologic Maps

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

Source Maps

The GRI GIS data include essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, cross sections, figures, and references.

The GRI team used the following source maps to produce the *Digital Geologic Map of Santa Monica Mountains National Recreation Area, California* (samo_geology.mxd).

Campbell, R. H., C. J. Wills, P. J. Irvine, and B. J. Swanson. Digital preparation by C. I. Gutierrez and M. D. O'Neal. 2014. Preliminary geologic map of the Los Angeles 30' × 60' quadrangle, California (scale 1:100,000; version 2.0). California Geological Survey and the US Geological Survey, Sacramento, California, and Washington, DC.

Tan, S. S., K. B. Clahan, C. S. Hitchcock, C. I. Gutierrez, and M. T. Mascorro. 2004. Geologic map of the Camarillo 7.5-minute quadrangle, Ventura County, California (scale 1:24,000; version 1.0). Preliminary Geologic Maps. California Geological Survey, Sacramento, California.

Wills, C. J., R. H. Campbell, and P. J. Irvine. 2012. Geologic map database of the Santa Monica Mountains region, Los Angeles and Ventura counties, California (scale 1:24,000). Unpublished data. California Geological Survey, Sacramento, California.

The data from Campbell et al. (2014) was used to cover the following (14) 7.5' quadrangles: Beverly Hills, Burbank, Calabasas, Canoga Park, Hollywood, Malibu Beach, Moon Park, Newbury Park, Point Dume, Simi Valley West, Thousand Oaks, Topanga, Triunfo Pass, and Van Nuys. The data from Wills et al. (2012) was used to cover the Camarillo and Point Mugu 7.5' quadrangles. All geologic features within these quadrangles were captured and included in the GRI GIS data (samo_geology.mxd). Folds and related fold map symbology were captured from Tan et al. (2004; scale 1:24,000).

In addition, the GRI team used the following source map to produce the *Digital Geohazards Map of Santa Monica Mountains National Recreation Area, California* (samo_geohazards.mxd).

Irvine, P. J., and T. P. McCrink. 2012. Landslide inventory of the Santa Monica Mountains region, Los Angeles and Ventura counties, California (scale 1:24,000). Unpublished data. California Geological Survey, Sacramento, California.

GRI GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is available at http://go.nps.gov/gridatamodel. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for the park using data model version 2.3. The GRI Geologic Maps website, http://go.nps.gov/geomaps, provides more information about GRI map products.

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

The following components are part of the GRI GIS data:

- A GIS readme file (samo_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 (tables 5 and 6);

- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information document (samo_geology.pdf) that contains information captured from source maps;
- ESRI map documents (samo_geology.mxd; samo_geohazards.mxd) that display the GRI GIS data; and
- A KML/KMZ version of the map data viewable in Google Earth.

Table 5. GRI GIS data layers for samo_geology.mxd.

Data Layer	On Poster?	Google Earth Layer?
Geologic Attitude and Observation Localities	No	No
Volcanic Line Features	Yes	Yes
Map Symbology	No	No
Folds	Yes	Yes
Faults	Yes	Yes
Linear Dikes	Yes	Yes
Geologic Contacts	Yes	Yes
Geologic Unit Labels	Yes	Yes
Geologic Units	Yes	Yes

Table 6. GRI GIS data layers for samo_geohazards.mxd.

Data Layer	On Poster?	Google Earth Layer?
Hazard Point Features	No, see fig. 32 for partial view of data	No
Hazard Area Feature Boundaries	No, see fig. 32 for partial view of data	Yes
Hazard Area Features	No, see fig. 32 for partial view of data	Yes

GRI Poster

A poster of the GRI GIS data (samo_geology.mxd) draped over shaded relief of the park and surrounding area is included with this report. Not all GIS feature classes are included on the poster (table 5). 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 set, but are available online from a variety of sources. Contact GRI for assistance locating these data. No poster was prepared for the geohazards data (samo_geohazards.mxd).

Use Constraints

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

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

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

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Additional References

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

California Geological Survey Regulatory Maps

- http://maps.conservation.ca.gov/cgs/informationwarehouse/index.html (includes seismic hazards, landslides, liquefaction, and fault evaluations)

Earthquake Hazard Information

- California Geological Survey earthquake information: http://www.conservation.ca.gov/cgs/geologic_hazards/earthquakes/Pages/index.aspx
- California Geological Survey fault activity maps: http://www.conservation.ca.gov/cgs/cgs_history/Pages/2010_faultmap.aspx (zoom in for the park area or other areas within the state). Also, an interactive map viewer: 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 Geological Survey map showing earthquake shaking potential for California: 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 Office of Emergency Services: http://myhazards.caloes.ca.gov/ (for discovering the hazards that exist in an area and how to reduce risk)
- Earthquake Country Alliance: http://www.earthquakecountry.org/ (earthquake hazards and preparedness in California)
- NPS Geologic Resources Division seismic monitoring information: http://go.nps.gov/geomonitoring
- Southern California Earthquake Center: http://www.scec.org/ucerf (forecast of earthquakes)
- Southern California Earthquake Data Center significant earthquakes and faults: http://scedc.caltech.edu/significant/fault-index.html (primary archive of seismological data for southern California)
- US Geological Survey: http://earthquake.usgs.gov/earthquakes/states/index.php?regionID=5 (California earthquake information)

ShakeMaps/Earthquake Planning Scenarios

- 1971 San Fernando earthquake: http://earthquake.usgs.gov/earthquakes/shakemap/sc/shake/San_Fernando/
- 1994 Northridge earthquake: http://earthquake.usgs.gov/earthquakes/shakemap/sc/shake/Northridge/
- 2008 ShakeOut Scenario: http://earthquake.usgs.gov/earthquakes/shakemap/sc/shake/shakeout2_full_se/
- 2014 Encino earthquake: http://earthquake.usgs.gov/earthquakes/shakemap/sc/shake/15476961/
- Santa Monica Mountains, magnitude 6.6 earthquake: ftp://ftp.consrv.ca.gov/pub/dmg/rgmp/CalEMA2009/Appendix%20A/S19%20Santa%20Monica%20Fault%20Scenario.pdf

Tsunami Information

- California Emergency Management Agency earthquake and tsunami hazards and mitigation information: http://hazardmitigation.calema.ca.gov/hazards/natural/seismic/hazards
- California Geological Survey tsunami inundation maps and information: http://maps.conservation.ca.gov/cgs/informationwarehouse/index.html http://www.conservation.ca.gov/cgs/geologic_hazards/Tsunami/Inundation_Maps/Pages/index.aspx
- NOAA's National Weather Service, Pacific Tsunami Warning Center: http://ptwc.weather.gov/

Landslide Resources

- California Geological Survey: http://www.conservation.ca.gov/cgs/geologic_hazards/landslides/Pages/LandslideTypes.aspx

- NPS Geologic Resources Division: http://go.nps.gov/geohazards http://go.nps.gov/monitor_slopes
- US Geological Survey: http://landslides.usgs.gov/

Climate Change Resources

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

Geological Surveys and Societies

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

Geology of National Park Service Areas

- NPS Geologic Resources Division—*Energy and Minerals, Active Processes and Hazards, and Geologic Heritage*: http://go.nps.gov/geology/
- NPS Geologic Resources Inventory: http://go.nps.gov/gri
- NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program: http://go.nps.gov/gip
- NPS Views program (geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a variety of geologic parks): http://go.nps.gov/views

NPS Resource Management Guidance and Documents

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

US Geological Survey Reference Tools

- California Seafloor Mapping Program: http://walrus.wr.usgs.gov/mapping/csmp/ http://www.opc.ca.gov/2010/03/mapping-californias-seafloor-2/
- Geologic glossary (simplified definitions): http://geomaps.wr.usgs.gov/parks/misc/glossarya.html
- Geologic names lexicon (Geolex; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html
- Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/
- GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")
- National geologic map database (NGMDB): http://ngmdb.usgs.gov/
- Publications warehouse (many publications available online): http://pubs.er.usgs.gov
- Tapestry of time and terrain (descriptions of physiographic provinces): http://tapestry.usgs.gov/Default.html

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting for Santa Monica Mountains National Recreation Area, held on 7 May 2008, or the follow-up report writing conference call, held on 17 November 2015. 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.

2008 Scoping Meeting Participants

Name	Affiliation	Position
John Alderson	Los Angeles County Museum	Research Associate/Invertebrate Paleontology
Lane Cameron	NPS Mediterranean Coast Network	Network Coordinator
Brendan Clarke	Santa Monica Mountains National Recreation Area	GIS Technician
Guy Cochrane	US Geological Survey	Geophysicist/Coastal Marine Geologist
Gary Davis	National Park Service (retired)	Science Advisor
Eugene Fritsche	California State University Northridge	Professor Emeritus
Bruce Heise	NPS Geologic Resources Division	Geologist/GRI Program Coordinator
Pam Irvine	California Geological Survey	Senior Engineering Geologist
Denise Kamradt	Santa Monica Mountains National Recreation Area	GIS Specialist
Katie KellerLynn	Colorado State University	Geologist/Research Associate
Stephanie Kyriazis	Santa Monica Mountains National Recreation Area	Interpreter
Greg Mack	NPS Pacific West Region	Geologist
John Minch	Santa Barbara Museum of Natural History	Dibblee Map Editor
Tarja Sagar	Santa Monica Mountains National Recreation Area	Biological Science Technician
Ray Sauvajot	Santa Monica Mountains National Recreation Area	Supervisory Ecologist
Tony Valois	Santa Monica Mountains National Recreation Area	Biological Science Technician
Chris Wills	California Geological Survey	Senior Engineering Geologist

2015 Conference Call Participants

Name	Affiliation	Position
Pam Irvine	California Geological Survey	Senior Engineering Geologist
Denise Kamradt	Santa Monica Mountains National Recreation Area	GIS Specialist
Katie KellerLynn	Colorado State University	Geologist/Research Associate
Jason Kenworthy	NPS Geologic Resources Division	Geologist/GRI Reports Coordinator
Vincent Santucci	NPS Geologic Resources Division	Geologist/Washington Liaison
Chris Wills	California Geological Survey	Supervising Engineering Geologist

Appendix B: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to National Park Service minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of August 2016. Contact the NPS Geologic Resources Division for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Paleontology	**National Parks Omnibus Management Act of 1998, 16 USC § 5937** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa et seq.** provides for the management and protection of paleontological resources on federal lands.	**36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted. Regulations in association with 2009 PRPA are being finalized (August 2016).	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.
Rocks and Minerals	**NPS Organic Act, 16 USC § 1 et seq.** directs the NPS to conserve all resources in parks (including rock and mineral resources), unless otherwise authorized by law.	**36 CFR § 2.1** prohibits possessing, destroying, disturbing mineral resources… in park units. **Exception: 36 CFR § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, or Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
Park Use of Sand and Gravel	**Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: -only for park administrative uses; -after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment; -after finding the use is park's most reasonable alternative based on environment and economics; -parks should use existing pits and create new pits only in accordance with park-wide borrow management plan; -spoil areas must comply with Part 6 standards; and -NPS must evaluate use of external quarries. Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Upland and Fluvial Processes	**Rivers and Harbors Appropriation Act of 1899, 33 USC § 403** prohibits the construction of any obstruction on the waters of the United States not authorized by congress or approved by the USACE. **Clean Water Act 33 USC § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US [including streams]). **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also **D.O. 77-2**) **Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also D.O. 77-1)	None applicable.	**Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems. **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks, unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding. **Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human-caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams. **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include…erosion and sedimentation…processes. **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester. **National Parks Omnibus Management Act of 1998, 16 USC § 5937** protects the confidentiality of the nature and specific location of cave and karst resources.	**36 CFR § 2.1** prohibits possessing/destroying/disturbing…cave resources…in park units. **43 CFR Part 37** states that all NPS caves are "significant" and sets forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Soils	**Soil and Water Resources Conservation Act, 16 USC §§ 2011–2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources. **Farmland Protection Policy Act, 7 USC § 4201 et. seq**. requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).	**7 CFR Parts 610 and 611** are the US Department of Agriculture regulations for the Natural Resources Conservation Service. Part 610 governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. Part 611 governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements.	**Section 4.8.2.4** requires NPS to -prevent unnatural erosion, removal, and contamination; -conduct soil surveys; -minimize unavoidable excavation; and -develop/follow written prescriptions (instructions).
Coastal Features and Processes	**NPS Organic Act, 16 USC § 1 et. seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). **Coastal Zone Management Act, 16 USC § 1451 et. seq.** requires Federal agencies to prepare a consistency determination for every Federal agency activity in or outside of the coastal zone that affects land or water use of the coastal zone. **Clean Water Act, 33 USC § 1342/Rivers and Harbors Act, 33 USC 403** require that dredge and fill actions comply with a Corps of Engineers Section 404 permit. **Executive Order 13089 (coral reefs) (1998)** calls for reduction of impacts to coral reefs. **Executive Order 13158 (marine protected areas) (2000)** requires every federal agency, to the extent permitted by law and the maximum extent practicable, to avoid harming marine protected areas.	**36 CFR § 1.2(a)(3)** applies NPS regulations to activities occurring within waters subject to the jurisdiction of the US located within the boundaries of a unit, including navigable water and areas within their ordinary reach, below the mean high water mark (or OHW line) without regard to ownership of submerged lands, tidelands, or lowlands. **36 CFR § 5.7** requires NPS authorization prior to constructing a building or other structure (including boat docks) upon, across, over, through, or under any park area.	**Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.8.1** requires NPS to allow natural geologic processes to proceed unimpeded. NPS can intervene in these processes only when required by Congress, when necessary for saving human lives, or when there is no other feasible way to protect other natural resources/ park facilities/ historic properties. **Section 4.8.1.1** requires NPS to: -Allow natural processes to continue without interference, -Investigate alternatives for mitigating the effects of human alterations of natural processes and restoring natural conditions, -Study impacts of cultural resource protection proposals on natural resources, -Use the most effective and natural-looking erosion control methods available, and -Avoid putting new developments in areas subject to natural shoreline processes unless certain factors are present.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Climate Change	**Secretarial Order 3289** (Addressing the Impacts of Climate Change on America's Water, Land, and Other Natural and Cultural Resources) (2009) requires DOI bureaus and offices to incorporate climate change impacts into long-range planning; and establishes DOI regional climate change response centers and Landscape Conservation Cooperatives to better integrate science and management to address climate change and other landscape scale issues. **Executive Order 13653** (Preparing the United States for the Impacts of Climate Change) (2013) outlines Federal agency responsibilities in the areas of supporting climate resilient investment; managing lands and waters for climate preparedness and resilience; providing information, data and tools for climate change preparedness and resilience; and planning. **Executive Order 13693** (Planning for Federal Sustainability in the Next Decade) (2015) established to maintain Federal leadership in sustainability and greenhouse gas emission reductions. **President's Climate Action Plan** (2013), http://www.whitehouse.gov/sites/default/files/image/president27sclimateactionplan.pdf	None applicable.	**Section 4.1** requires NPS to investigate the possibility to restore natural ecosystem functioning that has been disrupted by past or ongoing human activities. This would include climate change, as put forth by Beavers et al. (in review). **NPS Climate Change Response Strategy** (2010) describes goals and objectives to guide NPS actions under four integrated components: science, adaptation, mitigation, and communication. **Policy Memo 12-02** (Applying National Park Service Management Policies in the Context of Climate Change) (2012) applies considerations of climate change to the impairment prohibition and to maintaining "natural conditions". **Policy Memo 14-02** (Climate Change and Stewardship of Cultural Resources) (2014) provides guidance and direction regarding the stewardship of cultural resources in relation to climate change. **Policy Memo 15-01** (Climate Change and Natural Hazards for Facilities) (2015) provides guidance on the design of facilities to incorporate impacts of climate change adaptation and natural hazards when making decisions in national parks. **DOI Manual Part 523, Chapter 1** establishes policy and provides guidance for addressing climate change impacts upon the Department's mission, programs, operations, and personnel. **Revisiting Leopold: Resource Stewardship in the National Parks** (2012) will guide US National Park natural and cultural resource management into a second century of continuous change, including climate change. **Climate Change Action Plan** (2012) articulates a set of high-priority no-regrets actions the NPS will undertake over the next few years **Green Parks Plan** (2013) is a long-term strategic plan for sustainable management of NPS operations.

NPS 638/134114, September 2016

National Park Service
U.S. Department of the Interior

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

www.nature.nps.gov

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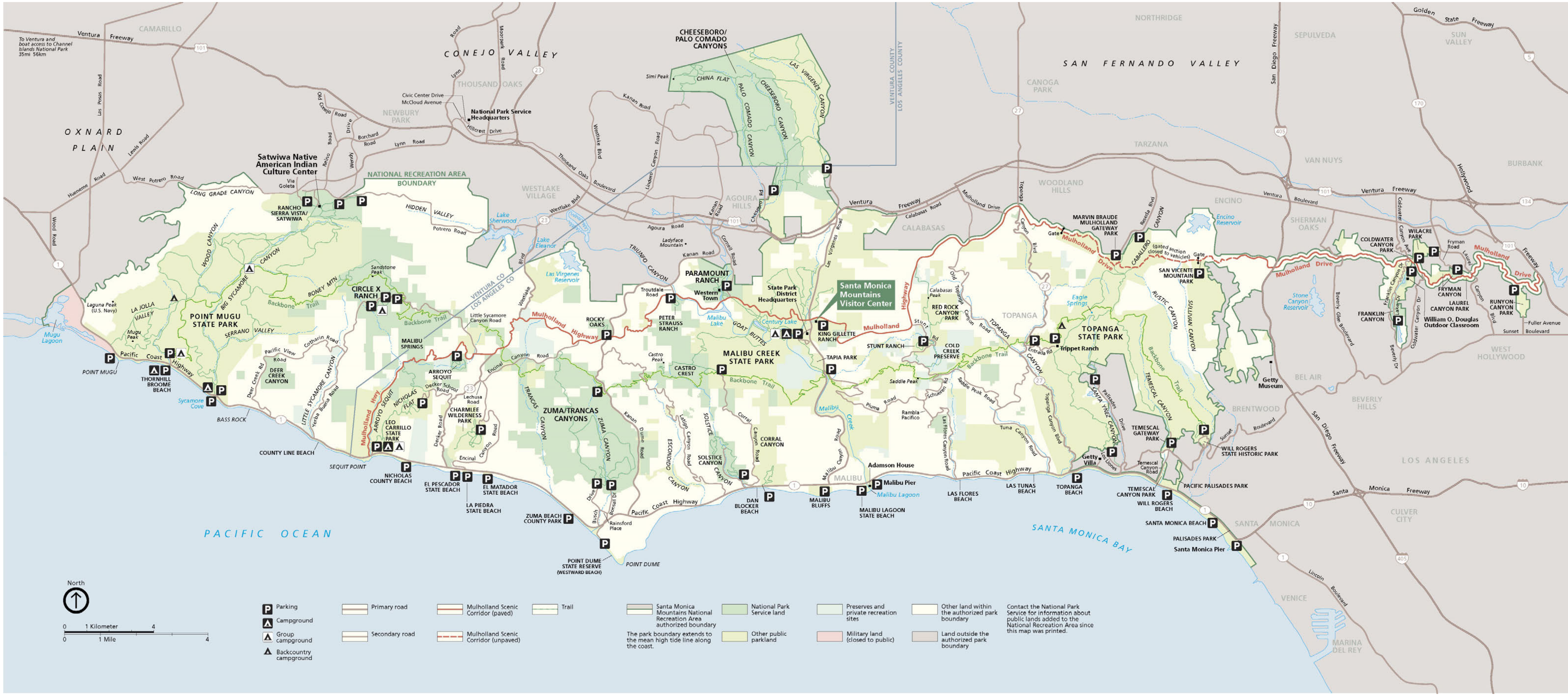


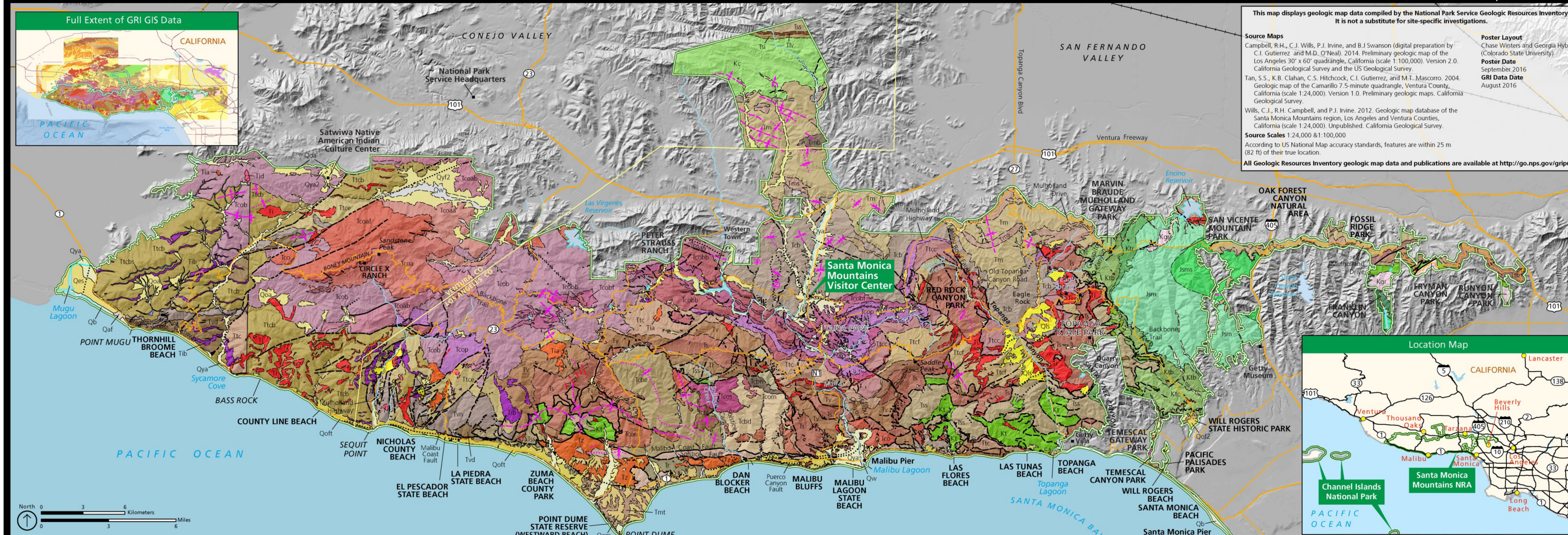
Figure 1. Map of Santa Monica Mountains National Recreation Area. The park consists of a web of protected places. Twenty different landowner types, including the entire City of Malibu, and more than 70 stakeholder groups share responsibilities and jurisdiction within the park's authorized boundary. A total of 62,020 ha (153,250 ac) are divided among private landowners, local parks, California State Parks, and the National Park Service. The National Park Service is steward of 9,510 noncontiguous hectares (23,500 ac) (National Park Service 2015a). National Park Service map available at https://www.nps.gov/hfc/cfm/carto.cfm.

Geologic Map of Santa Monica Mountains National Recreation Area

California

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science



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

Source Maps

Campbell, R.H., C.J. Wills, P.J. Irvine, and B.J Swanson (digital preparation by C.I. Gutierrez and M.D. O'Neal). 2014. Preliminary geologic map of the Los Angeles 30' x 60' quadrangle, California (scale 1:100,000). Version 2.0. California Geological Survey and the US Geological Survey.

Tan, S.S., K.B. Clahan, C.S. Hitchcock, C.I. Gutierrez, and M.T. Mascorro. 2004. Geologic map of the Camarillo 7.5-minute quadrangle, Ventura County, California (scale 1:24,000). Version 1.0. Preliminary geologic maps. California Geological Survey.

Wills, C.J., R.H. Campbell, and P.J. Irvine. 2012. Geologic map database of the Santa Monica Mountains region, Los Angeles and Ventura Counties, California (scale 1:24,000). Unpublished. California Geological Survey.

Source Scales 1:24,000 &1:100,000

According to US National Map accuracy standards, features are within 25 m (82 ft) of their true location.

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

Poster Layout
Chase Winters and Georgia Hybels (Colorado State University)
Poster Date
September 2016
GRI Data Date
August 2016

NPS Boundary

Infrastructure

- Point of interest
- City
- River or stream
- Road/trail
- Railroad

Volcanic Line Features

- Tuff marker bed, known or certain

Folds

- Anticline, known or certain, dashed where approximate, dotted where concealed
- Syncline, known or certain, dashed where approximate, dotted where concealed
- Overturned anticline, concealed

Faults

- Thrust fault, known or certain, dashed where approximate, short dashed where inferred, dotted where concealed
- Thrust fault, approximate and queried
- Reverse fault, approximate
- Unknown offset/displacement, known or certain, dashed where approximate, short dashed where inferred, dotted where concealed
- Unknown offset/displacement, approximate and queried
- Unknown offset/displacement, inferred and queried
- Detachment fault/decollement, known or certain, dashed where approximate, short dashed where inferred, dotted where concealed

Linear Dikes

- Ti - Intrusive rocks, undivided (middle Miocene), known or certain, dashed where approximate

Geologic Contacts

- Known or certain, dashed where approximate, short dashed where inferred, dotted where concealed
- Approximate and queried
- Inferred and queried
- Water or shoreline, dashed where approximate

Geologic Units

	Water
Qaf	Artificial fill (late Holocene)
Qa	Alluvium (late Holocene)
Qw	Wash deposits (late Holocene)
Qb	Beach deposits (late Holocene)
Qe	Eolian deposits (late Holocene)
Qf	Alluvial fan (Holocene)
Qes	Active coastal estuarine deposits (Holocene)
Qw1	Holocene wash deposit of the Oxnard Plain (Holocene)
Qls	Landslide deposits (Holocene and late Pleistocene?)
Qya	Young alluvium, undivided (Holocene and late Pleistocene)
Qya2	Young alluvium, Unit 2 (late Pleistocene)
Qya1	Young alluvium, Unit 1 (late Pleistocene)
Qyf	Young alluvial-fan deposits, undivided (Holocene and late Pleistocene)
Qyf2	Young alluvial-fan deposits, Unit 2 (late Pleistocene to Holocene)
Qoft	Alluvial fan deposits on wave-cut surface (late Pleistocene to Holocene)
Qoa	Old alluvium, undivided (middle to late Pleistocene)
Qof4	Old fan deposits, Unit 4 (late Pleistocene)
Qof2	Old fan deposits, Unit 2 (late Pleistocene)
Qof1	Old fan deposits, Unit 1 (late Pleistocene)
Qom	Old shallow marine deposits on wave-cut surface (late Pleistocene)
QTms	Sedimentary rocks of the Pacific Palisades area (late Pliocene to early Pleistocene)
Tm	Modelo Formation, undivided (late and middle Miocene)
Tmd	Modelo Formation, diatomaceous shale (late and middle Miocene)
Tms	Modelo Formation, sandstone (late and middle Miocene)
Tmb	Modelo Formation, "burnt shale" (late and middle Miocene)
Tmt	Monterey Shale, undivided (late, middle, and early Miocene)
Tmtd	Monterey Shale, deformed (middle and early Miocene)
Tcb	Calabasas Formation, undivided (early late Miocene and late middle Miocene)
Tcbs	Calabasas Formation, Stokes Canyon Breccia Member (late middle Miocene)
Tcbmp	Calabasas Formation, Mesa Peak Breccia Member (late middle Miocene)
Tcbn	Calabasas Fromation, Newell Sandstone Member (late middle Miocene)
Tcbd	Calabasas Formation, Dry Canyon Sandstone Member (late middle Miocene)
Tcbl	Calabasas Formation, Latigo Canyon Breccia Member (late middle Miocene)
Tcbe	Calabasas Formation, Escondido Canyon Shale Member (late middle Miocene)
Tr	Trancas Formation, undivided (middle and early Miocene)
Tra	Trancas Formation, quartz-bearing calcarenites (middle and early Miocene)
Tz	Zuma Volcanics (middle and early Miocene)
Tt	Topanga Group, undivided (middle and early Miocene)
Ttb	Topanga Group, intrusive and extrusive volcanic rocks (middle and early Miocene)
Tco	Conejo Volcanics, undivided (middle Miocene)
Tcod	Conejo Volcanics, dacite-bearing upper zone (middle Miocene)
Tcoa	Conejo Volcanics, andesitic central zone (middle Miocene)
Tcoaf	Conejo Volcanics, andesitic central zone, andesitic flows (middle Miocene)
Tcoaa	Conejo Volcanics, andesitic central zone, andesitic agglomerate (middle Miocene)
Tcoab	Conejo volcanics, andesitic central zone, andesite breccia (middle Miocene)
Tcob	Conejo Volcanics, basaltic lower zone, basalt and andesitic basalt (middle Miocene)
Tcoadb	Conejo Volcanics, mixture of andesitic and dacitic flow breccias with some flows (middle middle Miocene)
Tcodb	Conejo Volcanics, dacitic flow breccias with some flows (middle middle Miocene)
Tcobf	Conejo Volcanics, basaltic lower zone, basalt and andestic basalt, basalt flows (middle Miocene)
Tcobb	Conejo Volcanics, basaltic lower zone, basalt and andesitic basalt, basaltic breccia (middle Miocene)
Tcop	Conejo Volcanics, basaltic lower zone, pillow basalt (middle Miocene)
Tcobz	Conejo Volcanics, basaltic lower zone, basaltic sand (middle Miocene)
Tcom	Conejo Volcanics, Malibu Bowl Tongue (middle Miocene)
Tcos	Conejo Volcanics, Solstice Canyon Tongue (middle Miocene)
Tcor	Conejo Volcanics, Ramera Canyon Tongue (middle Miocene)
Ti	Intrusive rocks, undivided (middle Miocene)
Tid	Intrusive rocks, dacite (middle Miocene)
Tia	Intrusive rocks, andesitic (middle Miocene)
Tib	Intrusive rocks, basaltic (middle Miocene)
Tim	Mixed rocks (middle Miocene and early or early middle Miocene)
Ttc	Topanga Canyon Formation, undivided (middle and early Miocene)
Ttcc	Topanga Canyon Formation, Cold Creek Member (middle and early Miocene)
Ttcf	Topanga Canyon Formation, Fernwood Member (middle and early Miocene)
Ttcs	Topanga Canyon Formation, Saddle Peak Member (middle and early Miocene)
Ttcb	Topanga Canyon Formation, Big Sycamore Member (middle and early Miocene)
Ttcbs	Topanga Canyon Formation, Big Sycamore Member, prominent sandstone bed (early middle Miocene)
Ttce	Topanga Canyon Formation, Encinal Member (middle and early Miocene)
Tv	Valqueros Formation, undivided (early Miocene and Oligocene)
Tvn	Vaqueros Formation, San Nicholas Member (early Miocene and Oligocene)
Tvd	Vaqueros Formation, Danielson Member (early Miocene and Oligocene)
Ts	Sespe Formation, undivided (early Miocene, Oligocene, and late Eocene)
Tsp	Sespe Formation, Piuma Member (early Miocene)
Tl	Llajas Formation (early to middle Eocene)
Tss	Santa Susana Formation (late Paleocene to early Eocene)
Tssl	Santa Susana Formation, limestone (late Paleocene to early Eocene)
Tlv	Las Virgenes Sandstone (early(?) Paleocene)
Tsi	Simi Conglomerate, undivided (Paleocene)
Kc	Chatsworth Formation (Late Cretaceous)
Kt	Tuna Canyon Formation, undivided (Late Cretaceous)
Kte	Tuna Canyon Formation, informal member 'e' (Late Cretaceous)
Ktd	Tuna Canyon Formation, informal member 'd' (Late Cretaceous)
Ktc	Tuna Canyon Formation, informal member 'c' (Late Cretaceous)
Ktb	Tuna Canyon Formation, informal member 'b' (Late Cretaceous)
Ktr	Trabuco Formation (Late Cretaceous)
Kgr	Granitic rocks (Late Cretaceous)
Jsm	Santa Monica Slate, undivided (Late Jurassic)
Jsms	Santa Monica Slate, spotted slate (Late Jurassic)
Jsmp	Santa Monica Slate, phyllite (Late Jurassic)