National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Redwood National and State Parks

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2021/2314

ON THE COVER

Photograph of Mill Creek. A tributary of the Smith River, Mill Creek flows in the northern part of the parks within Jedediah Smith Redwoods and Del Norte Coast Redwoods State Parks. Its drainage area is 96 km^2 (37 mi^2).

NPS photograph by John Chao, modified to fit report format.

THIS PAGE

Photograph of the mouth of the Klamath River from the Klamath River Overlook. The Klamath River Overlook is high up on a bluff on the north side of the mouth of the Klamath River. On a clear day, the overlook provides a superb view of the river where it enters the Pacific Ocean. The bedrock underlying the overlook is the Franciscan Complex, mélange unit of Crescent City (map unit KJfmc). The spit that separates the estuary from the ocean is composed of beach sand (Qbs).

Photograph by Katie KellerLynn (Colorado State University).

Redwood National and State Parks

Geologic Resources Inventory Report

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

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

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

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

Views, statements, findings, conclusions, recommendations, and data in this report do not necessarily reflect views and policies of the National Park Service, U.S. Department of the Interior. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the U.S. Government.

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Contents

Figures

Tables

Executive Summary

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

This report synthesizes discussions from a scoping meeting for Redwood National and State Parks (referred to as the "parks" throughout this report) held in 2004 and a follow-up conference call in 2019. Two GRI–compiled GIS data sets of the geology and geohazards of the parks are the principal deliverables of the GRI. The GRI GIS data are available on the GRI publications website http://go.nps.gov/gripubs and through the NPS Integrated Resource Management Applications (IRMA) portal https://irma.nps.gov/App/Portal/Home. Enter "GRI" as the search text and select a park from the unit list. Writing of this report was based on those data and the interpretations of the source map authors (see "GRI Products" and "Acknowledgements").

A geologic map poster illustrates the geology GRI GIS data set and serves as a primary figure for this GRI report. No poster was prepared for the geohazards GRI GIS data set. Additionally, figure 7 of this report illustrates the locations of the major geologic features in the parks. Unlike the poster, which is divided into a northern and southern portion to show detail while accommodating the parks' length, figure 7 is a single-page, simplified map. The features labeled on figure 7 are discussed in the "Geologic History, Features, and Processes" chapter.

To provide a context of geologic time, this report includes a geologic time scale (see "Geologic History, Features, and Processes"). The parks' geologic story encompasses 200 million years, starting in the Jurassic Period. Following geologic practice, the time scale is set up like a stratigraphic column, with the oldest units at the bottom and the youngest units at the top. Organized in this manner, the geologic time scale table shows the relative ages of the rock units that underlie the parks and the unconsolidated deposits that lie at the surface. Reading the "Geologic Event" column in the table, from bottom to top, will provide a chronologic order of the parks' geologic history. The time scale includes only the map units within the parks that also appear on the geologic map poster; that is, map units of the geohazards data are not included.

Geology is a complex science with many specialized terms. This report provides definitions of geologic terms at first mention, typically in parentheses following the term. Geologic units in the GRI GIS data are referenced in this report using map unit symbols; for example, map unit **KJfrc** stands for the Cretaceous (**K**) and Jurassic (**J**) Franciscan Complex (**f**), Redwood Creek schist (**rc**), which underlies a portion of the Redwood Creek watershed (see "GRI Products").

This report contains the following chapters:

Introduction to the Geologic Resources Inventory—This chapter provides background information about the GRI, highlights the GRI process and products, and recognizes GRI collaborators.

Geologic Heritage—This chapter highlights the significant geologic features, landforms, landscapes, and stories of the parks preserved for their heritage values. These stories include the California Gold Rush (1848–1855), establishment of the parks, more than 40 years of geomorphic research, and the lineage of the coast redwood (*Sequoia sempervirens*). The chapter draws connections between geologic resources and other park resources. It also highlights the parks' physiographic setting in the northern Coast Ranges of California and describes the parks' location and boundaries.

Geologic History, Features, and Processes—This chapter describes the geologic features and processes at the parks and highlights them in a context of geologic time and plate tectonics (a scientific theory of how Earth works). The features and processes are discussed more-or-less in order of geologic age (oldest to youngest). The oldest rocks in the parks are composed of the Josephine ophiolite ("**J**" map units), which represents uplifted seafloor that formed in a developing subduction zone (where one of Earth's tectonic plates dives beneath another). These Jurassic rocks are between 163.5 million and 145 million years old. The youngest geologic units mapped within the parks are surficial deposits that formed in stream channels and on beaches during the Quaternary Period (the past 2.6 million years). Though not mapped as part of the GRI GIS data, tsunami deposits, which were preserved in freshwater marshes during the past 3,000 years, also are discussed.

Geologic Resource Management Issues—This chapter discusses management issues related to the parks' geologic resources (features and processes). These issues are ordered alphabetically, not with respect to management priority, and include the following: climate change, coastal resources management, dam removal in the Klamath River watershed, landslides, marijuana cultivation sites, offshore geologic resource management, Quaternary faults and earthquakes, Redwood Creek and the Clean Water Act, Redwood Creek streamflow, restoration of Redwood Creek watershed, restoration of Redwood Creek estuary, and tsunamis. Information about these issues was compiled from the 2004 scoping summary (Covington 2004), the parks' foundation document (National Park Service 2016a), field notes from a visit to the parks in October 2019, notes from the 2019 GRI conference call, research associated with preparation of this report, and input from reviewers.

Guidance for Resource Management—This chapter is a follow up to the "Geologic Resource Management Issues" chapter. It provides the parks' managers with a variety of ways to find and receive management assistance with geologic resources. It also provides a list of laws, regulations, and NPS policies that specifically apply to geologic resources in the National Park System. The NPS Geologic Resources Division can provide policy assistance and technical expertise regarding the parks' geologic resources.

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

Introduction to the Geologic Resources Inventory

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

GRI Products

Starting in 2004, the GRI team—which is a collaboration between the National Park Service, Geologic Resources Division, and Colorado State University, Department of Geosciences—completed four tasks as part of the GRI for Redwood National and State Parks (referred to as the "parks" throughout this report): (1) conduct a scoping meeting and provide a scoping summary, (2) provide digital geologic map data in a geographic information system (GIS), (3) provide a poster displaying the GRI GIS data, and (4) provide a GRI report.

GRI products are available on the GRI publications website (http://go.nps.gov/gripubs) and through the NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/). Enter "GRI" as the search text and select a park from the unit list. Additional information regarding the GRI, including contact information, is available at http://go.nps.gov/gri.

The GRI products have the following use constraint: Graphic and written information is not a substitute for site-specific investigations. Ground-disturbing activities should be neither permitted nor denied based upon the information provided by the GRI. Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features in the GRI GIS data and on the poster. Based on the source map scales—1;24,000 for Dell'Osso et al. (2002a, 2002b) and 1:100,000 for Delattre and Rosinski (2012)—and US National Map Accuracy Standards, geologic features represented in the GRI GIS data and on the poster are expected to be horizontally within 12 m (40 ft) and 51 m (167 ft) of their true locations, respectively.

GRI Scoping Meeting

On 2–3 March 2004, the National Park Service held a scoping meeting in Ashland, Oregon. The meeting brought together geologists, other scientists, and data managers from the National Park Service, US Geological Survey (USGS), and US Department of Agriculture (USDA) Natural Resources Conservation Service, who reviewed and assessed available geologic maps, developed a geologic mapping plan, and discussed geologic features, processes, and resource management issues to be included in the final GRI report. A scoping summary (Covington 2004) records the findings of that meeting.

GRI GIS Data

Following the scoping meeting, the GRI team compiled two GRI GIS data sets for the parks: redw_geology and redw_geohazards. These data are the principal deliverable of the GRI. The GRI team did not conduct any new geologic mapping but compiled existing geologic information (i.e., paper maps and/or digital data) into the GRI GIS data (fig. 1). Scoping participants and the GRI team identified the best available source maps with respect to coverage (extent or area mapped), map scale, date of mapping, and compatibility of the mapping to the current geologic interpretation of an area.

The GRI ancillary map information document (redw_geology.pdf) includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, cross sections, figures, and references.

The GRI team standardizes map deliverables by using a data model. The GRI GIS data for the parks was compiled using data model version 2.3, which 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 used the following three maps to produce the GRI GIS data for the parks (fig. 1). The first two are part of the geology data set. The third composes the geohazards data set.

- Delattre and Rosinski (2012), *Preliminary Geologic Map of the Onshore Portions of the Crescent City and Orick 30' × 60' Quadrangles, California* (scale 1:100,000), provided geologic data for the northern and coastal portions of the parks.

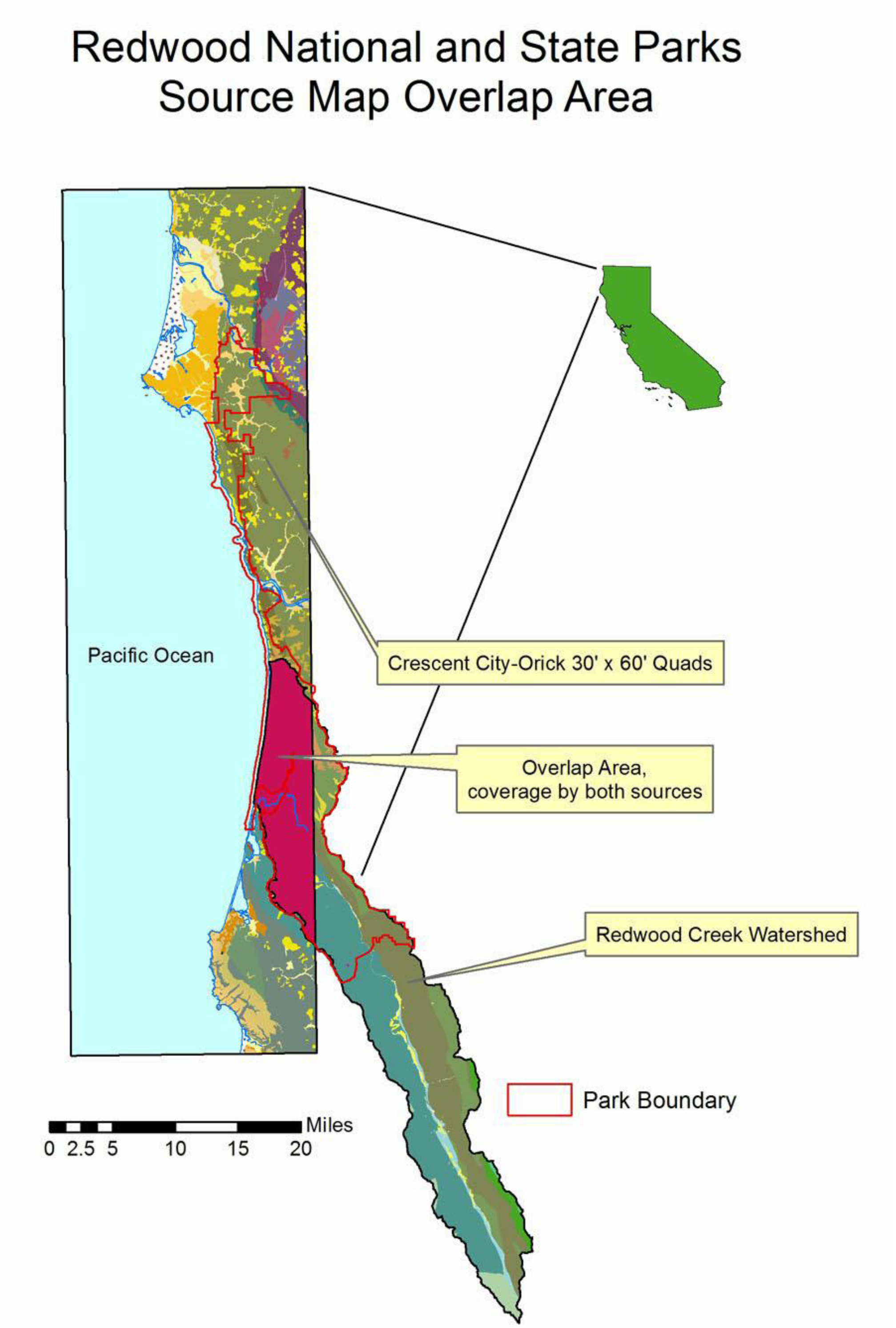

Figure 1. Index map of the GRI GIS data for the parks.
The figure displays the extent of GRI GIS data produced for Redwood National and State Parks. The red line delineates the parks' boundary. Map data by Delattre and Rosinski (2012) cover the Crescent City and Orick 30' × 60' quadrangles (scale 1:100,000). These data encompass coastal and other park areas not within the Redwood Creek watershed. Map data by Dell'Osso et al. (2002a, 2002b) cover the Redwood Creek watershed (scale 1:24,000). In the "overlap area," map data by Delattre and Rosinski (2012) was used in the geology GRI GIS data set whereas map data by Dell'Osso et al. (2002b) was used in the geohazards GRI GIS data set. GRI graphic by Greg Mack (NPS Pacific West Regional Office) and Stephanie O'Meara (Colorado State University).

- Dell'Osso et al. (2002a), Plate 1 of *Geologic and Geomorphic Features Related to Landsliding, Redwood Creek Watershed, Humboldt County, California* (scale 1:24,000), provided geologic data for the Redwood Creek watershed. In the geology data set, where mapping by Delattre and Rosinski (2012) overlaps the Redwood Creek watershed (see "overlap area" on fig. 1), the GRI team used the data by Delattre and Rosinski (2012) rather than Dell'Osso et al. (2002a). Falls et al. (2003) is the written report that accompanies the map by Dell'Osso et al. (2002a).
- Dell'Osso et al. (2002b), Plate 2 of *Relative Landslide Potential with Geologic and Geomorphic Features, Redwood Creek watershed, Humboldt County, California* (scale 1:24,000), provided landslide data for the Redwood Creek watershed, including the "overlap area" (fig. 1). Falls et al. (2003) is the written report that accompanies the map by Dell'Osso et al. (2002b).

Significantly, the maps by Dell'Osso et al. (2002a, 2002b), which cover the Redwood Creek watershed, were compiled from numerous sources including published (e.g., Harden et al. 1982; Kelsey and Cashman 1983; Kilbourne 1985) and unpublished maps and reports by the California Division of Mines and Geology, US Geological Survey, USDA Forest Service, and Redwood National Park. Although Dell'Osso et al. (2002a, 2002b) conducted and then compiled some geologic and geomorphic mapping, compilation of existing data and interpretation of aerial photographs represent the primary information sources.

The map by Delattre and Rosinski (2012) is a compilation of existing geologic mapping from many sources together with new mapping of Quaternary deposits in valleys and along the coast, as well as of selected larger landslides that could be reasonably displayed at a map scale of 1:100,000. The map by Delattre and Rosinski (2012) used and compiled the following mapping projects: Back (1957), Ristau (1979), Harper (1980), Woodward-Clyde Consultants (1980), Aalto (1981, 1989, 2006), Aalto et al. (1981), Aalto and Harper (1982), Davenport (1982, 1983a, 1983b, 1983c, 1984a, 1984b), Harden et al. (1982), Stone (1983), Evans (1984), Kelsey and Trexler (1989), Carver (1992), Cashman et al. (1995), Polenz and Kelsey (1999), Wills (2000), Dell'Osso et al. (2003), and Elder and Reichert (2010).

GRI Poster

A geologic map poster illustrates the geology GRI GIS data set and serves as a primary figure to accompany this GRI report. Because the parks are long and thin, the poster is divided into a northern and southern portion. The poster is not a substitute for the GIS data but is supplied as a helpful tool for office and field use and for users without access to ArcGIS. Not all GIS feature classes are included on the poster. Geographic information and selected park features have been added to the poster. Digital elevation data and added geographic information are not included in the GRI GIS data but are available online from a variety of sources. No poster was created for the geohazards GRI GIS data set.

GRI Report

On 18 November 2019, the GRI team hosted a follow-up conference call for park staff and others interested in the geologic resources of the parks (see "Acknowledgements"). The call provided an opportunity to get back in touch with park staff, introduce "new" (since the 2004 scoping meeting) staff to the GRI process, and update the list of geologic features, processes, and resource management issues for inclusion in the final GRI report.

This report is a culmination of the GRI process. It synthesizes discussions from the scoping meeting in 2004, the follow-up conference call in 2019, and additional geologic research. The selection of geologic features discussed in the report was guided by the previously completed GRI GIS data. Writing reflects these data and the geologic interpretations of the source map authors (i.e., Dell'Osso et al. 2002a, 2002b; Delattre and Rosinski 2012). Information from the parks' foundation document (National Park Service 2016a) was also included as applicable to the parks' geologic resources and resource management.

Geology is a complex science with many specialized terms. This report provides definitions of geologic terms at first mention, typically in parentheses following the term.

Geologic units in the GRI GIS data are referenced in this report using map unit symbols. For example, the Franciscan Complex, which underlies most of the parks, is divided into seven map units, each with a map unit symbol that starts "**KJf**." "**K**" represents the Cretaceous Period (145.0 million to 66.0 million years ago). "**J**" represents the Jurassic Period (201.3 million to 145.0 million years ago), and "**f**" stands for Franciscan. The letter "**f**" is followed by other letters representative of a particular unit's name; for example, **KJfbf** stands for the Franciscan Complex broken formation, which is composed of graywacke (hard, dense, dark gray) sandstone and underlies the northern portion of the parks (see poster). The Gold Bluffs in the parks consist of the Prairie Creek Formation (**QTpc**). "**Q**" represents the Quaternary Period (2.6 million to 11,700 years ago), and "**T**" represents Tertiary time (66.0 million to 2.6 million years ago). The letters "**pc**" stand for Prairie

Creek. The Prairie Creek Formation consists of weakly consolidated sand and gravel.

Acknowledgements

The GRI team thanks the participants of the 2004 scoping meeting (see "Scoping Participants" list, below) and 2019 conference call (see "Conference Call Participants" list, below) for their assistance in this inventory. These lists serve as a legacy record and reflect participants' affiliations and names at the time of scoping or conference call.

The GRI team acknowledges and thanks the many geologists and hydrologists who conducted work in Redwood National and State Parks, particularly the Redwood Creek watershed. *Redwood Creek Watershed Studies: Summary of Geomorphic Research at Redwood National Park* (Madej 2021) summarized this body of work.

The source maps for the GRI GIS data were compiled from numerous projects including published and unpublished maps and reports by many investigators from many agencies (see "GRI GIS Data"). Thanks to the California Geological Survey for its compilation of these geologic maps; this report and accompanying GIS data could not have been completed without that effort.

Thanks to Vicki Ozaki (Redwood National and State Parks) for her help, time, and guidance while writing this report and the suggestions she provided during the review process; her input provided a depth of information that would not have been included otherwise. Thanks to Justin Tweet (NPS Geological Resources Division) for providing information about *Sequoia* fossils throughout world, including within the National Park System. Thanks to Marc Delattre (California Geological Survey) for his input about landslides, sea stacks, and the Franciscan Complex broken formation. Thanks to Rebecca Beavers (NPS Geologic Resources Division and Climate Change Response Program), Dave Best (Redwood National and State Parks), Thom Curdts (Colorado State University), Karin Grantham (Redwood National and State Parks), and Steve Simon (NPS Geologic Resources Division) for their review of coastal-related sections of this report, input about shoreline length, and/or guidance on NPS regulatory authority of coastal and submerged lands. Thanks to Trista Thornberry-Ehrlich (Colorado State University) for producing many of the graphics in this report and her willingness and facility in "tweaking" them.

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Geologic Heritage

This chapter highlights the parks' geologic heritage and draws connections between geologic resources and other park resources and stories. Geologic heritage encompasses the significant geologic features, landforms, and landscapes of a park that are preserved for the full range of values that society places on them, including scientific, aesthetic, cultural, ecosystem, educational, and recreational. The NPS also identifies geologic heritage aspects of museum collections, soils, and scientific data sets.

Influence of Geology

The influence of underlying geology on the parks' landscape is undeniable (fig. 2). The topography, slope stability, character and location of stream channels, presence of sea stacks, types of soil that form, and vegetation that grows are all influenced by the parks' underlying rocks.

Evidence of the influence of geology is shown in the GRI GIS data, on the poster, and throughout this report, but but a few examples are highlighted here: First, although much of the parks' landscape is dominated by knobby, irregular, landslide-prone topography of the Franciscan Complex (see "Franciscan Complex"), Josephine ophiolite (see "Josephine Ophiolite"), which originally formed on the seafloor and is characteristic of the Klamath Mountains, underlies the northeastern portion of the parks. The ultramafic, or colloquially "serpentine," rocks and soils of the Josephine ophiolite have dramatic effects on vegetation. Many plants cannot grow in serpentine soils, leaving distinctive suites of plants to occupy serpentine habitats (Alexander et al. 2007). Second, south of Crescent City, California, a small portion of the parks' coast consists of the Battery Formation (see "Battery Formation and Marine Terraces"). Composed of a marine terrace (wave-cut platform) that formed via erosion of the shore, the surface of the formation now sits above sea level as a result of ongoing uplift. Third, in the Gold Bluffs area of the parks, the Prairie Creek Formation (see "Prairie Creek Formation") stands large, providing a stunning backdrop at Gold Bluffs Beach. The Gold Bluffs mark the ancestral mouth of the Klamath River, which shifted to its more northerly location during the past 700,000 years. These and other geologic features and processes are further described in the "Geologic History, Features, and Processes" chapter of this report.

Physiographic Setting

The parks are part of the California Coast Ranges, a northwest-oriented chain of nonvolcanic mountains bordering the Pacific Ocean. The Coast Ranges comprise a series of separate but parallel ranges and intervening valleys that span about 1,530 km (950 mi) from the Klamath Mountains near the California–Oregon border to the Transvers Ranges south of Santa Barbara, California. The Coast Ranges are commonly divided into a northern and southern portion; the dividing point is the depression containing San Francisco Bay. The parks are part of the northern Coast Ranges.

In most places, the mountains of the Coast Ranges run to the sea where wave erosion has carved a rugged and picturesque coast. Owing to ancient sea level changes and a rising land surface, marine terraces (steplike platforms) line much of the coast (see "Battery Formation and Marine Terraces"). In addition, streams have cut narrow canyons down to the shore (see "Fluvial Features and Processes"). Sandy beaches with sand dunes develop in some bays and near stream mouths (see "Coastal Features and Processes").

At 2,468 m (8,098 ft) above sea level, the highest point in the northern Coast Ranges is Mount Linn (southeast of the parks). Elevations within the parks range from below sea level (see "Offshore Geologic Features") to 944 m (3,097 ft) above sea level at Schoolhouse Peak (see poster). Despite modest elevations, local relief can be impressive, particularly along sea cliffs or within narrow, deeply incised stream gorges.

Park Location and Boundaries

The parks, which are in Del Norte and Humboldt Counties, California, are roughly equidistant between Portland, Oregon, and San Francisco, California. US Highway 101, also referred to as the "Pacific Coast Highway," provides access to the parks. The highway traverses about 2,700 km (1,700 mi) through Washington, Oregon, and California. In the vicinity of the parks, visitors pass through Crescent City, Klamath, and Orick, California as they travel south on Highway 101 (see poster). Between 2008 and 2018, an average of 436,940 people visited the parks annually (National Park Service 2019b).

The parks consist of one national park (Redwood National Park) and three state parks, from north to south, Jedediah Smith Redwoods, Del Norte Redwoods, and Prairie Creek Redwoods State Parks (see poster). Together, this four-park area encompasses

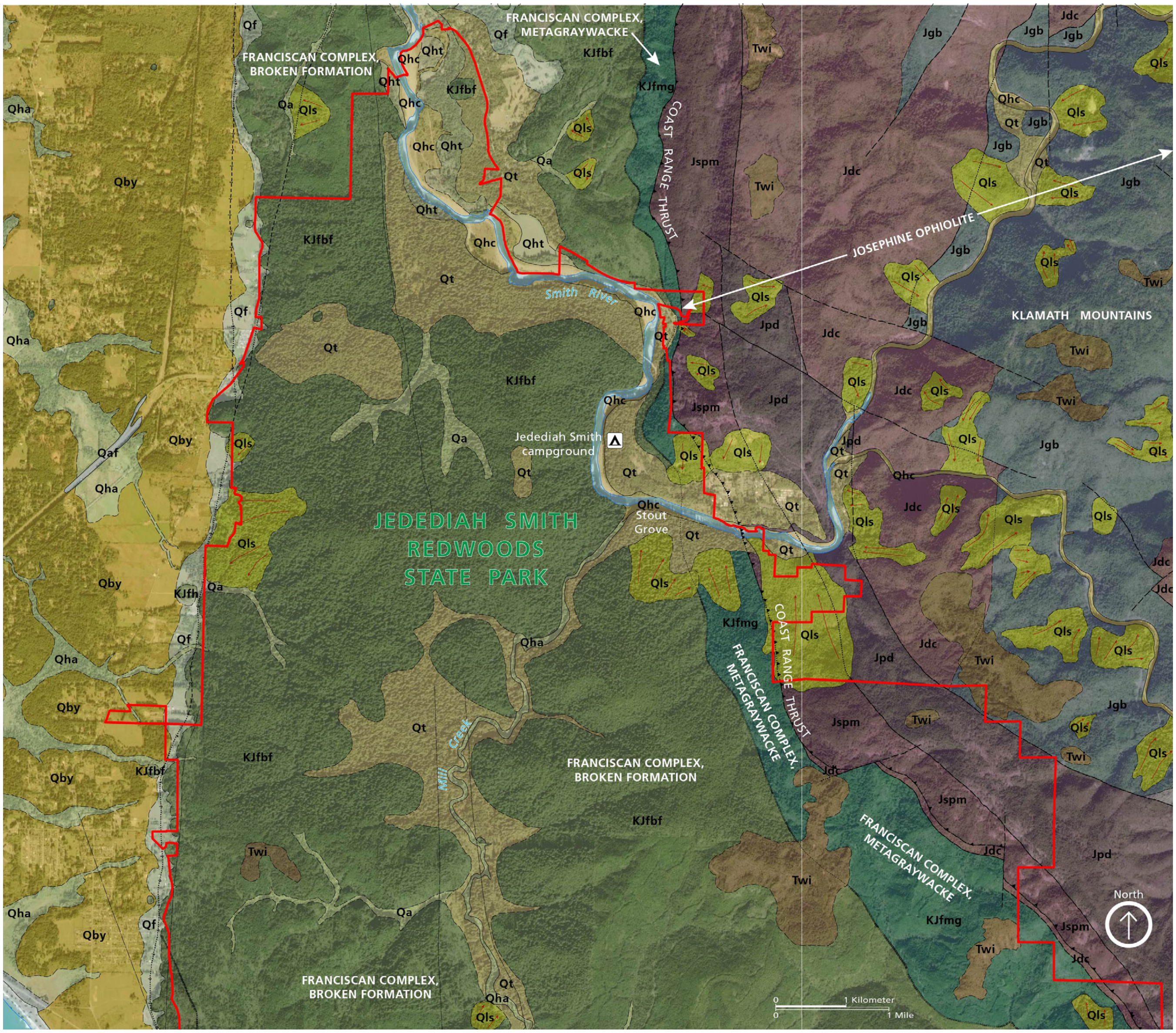

Figure 2. Geologic map of Jedediah Smith Redwoods State Park and vicinity.
Redwoods State Park—which consists of the Josephine ophiolite ("J" map units) and the Franciscan Complex, broken formation (KJfbf)—illustrates how underlying geology influences hillslopes, vegetation, and stream channels in the parks. The Klamath Mountains to the east of the state park are composed of hard rock (Josephine ophiolite) creating high mountains. In the Klamath Mountains, the narrow stream channels are confined in bedrock, and the forest consists of mixed conifers. To the west of the Josephine ophiolite, the Franciscan Complex, which creates much softer terrain with wider channels and floodplains, underlies the state park. Stout Grove and the Jedediah Smith campground are on low-lying floodplains and terraces (Qt). Solid stands of old growth redwood trees grow on the transition area between the Josephine ophiolite (Klamath Mountains) and Franciscan rocks (Coast Ranges); the transition area is marked by the Coast Range thrust and Franciscan Complex metagraywacke (KJfmg). Caption modified from text by Vicki Ozaki (Redwood National and State Parks, written communication, 18 August 2020). Graphic by Trista Thornberry-Ehrlich (Colorado State University) using GRI GIS data and ESRI ArcGIS World Imagery.

some 53,414 ha (131,983 ac) of which 29,023 ha (71,715 ac) are federally owned. The four-park area is a world heritage site and a biosphere reserve, designated by the United Nations Educational, Scientific and Cultural Organization (UNESCO) in 1980 and 1983, respectively.

The National Park Service and the California Department of Parks and Recreation jointly manage the four-park area for maximum resource protection. This partnership, which commenced in 1994, serves as a national model of collaborative management and landscape-scale resource protection (National Park Service 2016a).

The parks are the ancestral lands of the Yurok, Chilula, Hupa, and Tolowa people. The natural resources of the land and sea continue to provide spiritual, cultural, and physical sustenance to the descendants of these original residents. The National Park Service and the California Department of Parks and Recreation work with associated tribes through government-to-government consultation, partnerships, and formal agreements to respect the interests of these traditionally associated people and provide opportunities for visitors to learn about these cultures (National Park Service 2016a).

Approximately 570 ha (1,400 ac) of federal land and waters within Redwood National Park also are part of the Yurok Reservation. From the Pacific Ocean, these tribal lands run upstream along the Klamath River for 69 km (43 mi). The width of the tribal lands is 1.6 km (1.0 mi) on both sides of the river (see poster).

The parks' western boundary is in the Pacific Ocean. The western boundary of Redwood National Park is located 0.4 km (0.25 mi or 1,320 ft) offshore of the ordinary high-water mark of the Pacific Ocean. The water depths at this seaward park boundary are on the order of 10 to 12 m (33 to 39 ft) deep (Borgeld et al. 2007). With respect to the three state parks: Jedediah Smith Redwoods State Park has no coastal boundary, but both Del Norte Redwoods and Prairie Creek Redwoods State Parks do. The western boundaries of Del Norte Redwoods and Prairie Creek Redwoods State Parks are the ordinary high-water mark of the Pacific Ocean. The State of California has title to all submerged lands and the land below the mean high tide out to a distance of 3 miles. These lands, known as sovereign state lands, are administered by the California State Lands Commission but can be leased to other entities through a submerged lands lease.

The National Park Service exercises regulatory authority over these lands through authority granted by the state through a submerged lands lease. In 2002, the National Park Service entered into a 49-year lease for a large portion of offshore land within the congressionally authorized park boundary (Lease PRC8369.9). The lease area extends 1,000 feet seaward of mean high water (average of all the daily tidal high-water heights observed over a period of several years) rather than the full 1,320 feet of the park boundary. An area at the mouth of the Klamath River was excluded from the lease to avoid competing claims of the Yurok Tribe. Also, an area along Crescent Beach that was previously leased to the Crescent City Harbor District was excluded from the lease.

California state parks do not have an official boundary line in the sense that national parks do. Boundaries of national parks are established by Congress and modified under the authority of specific legislation. State parks are established by the state, but as lands are acquired for park purposes and placed under the jurisdiction of California State Parks, they automatically become part of the park. As such, state parks do not have the notion of an inholding (private lands within a park's legislative boundary). In national parks, the presence of an inholding provides the park specific authority to acquire it. State lands that are under the jurisdiction of other state agencies, but adjacent to or included within the bounding polygon of park lands, are not considered part of the park. Notable examples of this are sovereign state lands, including offshore, tidal, and submerged riverbeds. Land in the custody of California Department of Transportation for highway purposes is also excluded from the state park.

Because the ordinary high-water mark can move through time, the location of the state–federal boundary was originally ambulatory and vague. On 15 December 2014, the United States Supreme Court entered the joint supplemental decree submitted by the United States Solicitor General's Office and the California Attorney General's Office in the case of United States v. California, No. 5, Original, 381 US 139 (1965). This action by the United States Supreme Court permanently fixes the offshore boundary between the United States and California, resolving a dispute that began in 1935 with the discovery of oil in Wilmington, California.

For the most part, offshore rocks (referred to as "sea stacks" in this report; see "Coastal Features and Processes") and islands that lie above the ordinary high-water mark were withdrawn from sale, settlement, and entry, and therefore remain in the public domain and federally owned. The national park's 1968 enabling legislation includes many offshore rocks within the boundary but did not clearly transfer custody to the National Park Service, though provisions exist for the willing transfer of federal property to the Secretary of Interior (Dave Best, Redwood National and State

Parks, GIS and information management, written communication, 25 March 2021).

Offshore rocks along the parks' coastline are part of California Coastal National Monument, which is managed by the Bureau of Land Management. This national monument protects approximately 400 ha (1,000 ac) of offshore rocks and islands along the 1,800-km- (1,100-mi-) long California coast, as well as six units on the mainland, including Trinidad Head (and lighthouse) in Trinidad (south of the parks). The average size of these offshore rocks and islands is less than 0.03 ha (0.07 ac; Bureau of Land Management 2019).

Reading Rock State Marine Conservation Area and False Klamath Rock Special Closure are within the parks' boundary (National Park Service 2016a). These areas are part of a suite of marine reserves along California's coast where the harvest of marine resources is restricted or prohibited by the Marine Life Protection Act of 1999. California Department of Fish and Wildlife and California State Parks manage these areas.

Park Background and Establishment

Coastal exploration—for example, by Juan Rodríguez Cabrillo in 1542 (see GRI report about Cabrillo National Monument by KellerLynn 2018)—and overland exploration, for example, by Jedediah Strong Smith in 1828—heralded the arrival of prospectors and settlers to the Redwood coast. Believed to have been of Portuguese descent, Cabrillo was a soldier and explorer in service to Spain. Smith, who was born in Jericho (now Bainbridge), New York, was an American.

From across the nation and globe, people thronged to California's coast in the mid-1800s, arriving on the wave of the California Gold Rush (1848–1855). Del Norte County was the site of much prospecting for gold. Records show 5,382 mining claims on public land managed by the Bureau of Land Management and 315 mines listed by the US Geological Survey (The Diggings™ 2019). Thousands of miners, using sluice boxes, rockers, and panning, worked claims—primarily placers (concentrations of gold in beach or stream deposits)—along the Trinity and Klamath Rivers; the Trinity River is a principal tributary of the Klamath River, which is one of three major river systems associated with the parks. By contrast, prospectors found little extractable gold in Humboldt County. Nevertheless, the county's early history is tied to the gold rush. Gold seekers flocked to coastal towns, which became prosperous and notoriously rowdy (Clarke Historical Museum 2018).

The California Gold Rush led to a mass human migration westward, and the coast redwood (*Sequoia sempervirens*) offered early settlers a seemingly inexhaustible supply of lumber. By 1853, three years after gold was discovered along the Trinity River, nine lumber mills were in full operation in the bayside community of Eureka (Borgeld et al. 2007). Harvest of redwood trees accelerated by World War II, and deforestation spread as a building frenzy took hold following the war. Building continued through the economic surge of the 1950s. By the 1960s, nearly 90% of the old-growth redwood forest had been eliminated (Borgeld et al. 2007).

Formed in 1918, the Save the Redwoods League encouraged the State of California to establish Prairie Creek Redwoods State Park (in 1923), Del Norte Coast Redwoods State Park (in 1925), and Jedediah Smith Redwoods State Park (in 1929). Two famous vertebrate paleontologists—Henry Fairfield Osborn (American Museum of Natural History) and John Campbell Merriam (University of California, Berkeley)—were co-founders of the Save the Redwoods League; their profession as paleontologists, rather than biologists, is notable for the GRI.

In 1968, Congress protected lands adjacent to these three state parks with the creation of Redwood National Park and further expanded the boundary of the national park (by 50%) with the 1978 Redwood National Park Expansion Act (also known as the "Redwood Amendment"). The parks currently preserve about 16,000 ha (40,000 ac) of old-growth coast redwood—the tallest trees on Earth (fig. 3).

In the Redwood Creek watershed, large scale logging began after 1945 and by the time of park expansion in 1978, 81% of the watershed had been harvested (fig. 4). The parks occupy the lower 40% of the watershed, also referred to as a "basin," with the upper basin primarily in private ownership (Vicki Ozaki, Redwood National and State Parks, geologist, written communication, 19 August 2020). Most of the logging in the Redwood Creek watershed had taken place before the establishment of the California Forest Practice Rules, which implement the Z'berg-Nejedly Forest Practice Act of 1973. That act ensures that logging is done in a manner that will preserve and protect the state's fish, wildlife, forests, and streams. The California Department of Forestry and Fire Protection enforces the rules (California Department of Forestry and Fire Protection 2021).

Figure 3. Photo illustration of the height of a coast redwood.
From a seed no bigger than a tomato's, the coast redwood (Sequoia sempervirens) can grow to heights matching a 35-story skyscraper. The multi-colored building—the "Charleson" in Vancouver, British Columbia—is 43 stories. According to The Gymnosperm Database (Earle 2019), the tallest coast redwood is in a remote part of Redwood National Park. This enormous tree, named Hyperion, is 115.85 m (380.09 ft) tall and 4.84 m (15.88 ft) in diameter. To illustrate the height of redwood trees, a tree from the Tall Trees Grove in the parks has been "replanted" in this photograph. Graphic by Trista Thornberry-Ehrlich (Colorado State University) using a cityscape photograph by Katie KellerLynn (Colorado State University) taken in 2019 and an NPS photograph of Tall Trees Grove.

Figure 4. Photograph of logging road, circa 1970.
This photograph illustrates the extent of logging in the Redwood Creek watershed. The photo shows a site, which was later included in Redwood National Park in 1978, on the east side of Redwood Creek. Widespread construction of haul roads and smaller skid trails accompanied timber harvest. Photograph by Dave Van de Mark (Dave Van de Mark Photograph Collection), copyright, used by permission.

More than 40 Years of Geomorphic Research

Today, more than 40 years (since 1978) of geomorphic research support restoration efforts and guide land management decisions in the parks. *Redwood Creek Watershed Studies: Summary of Geomorphic Research at Redwood National Park* (Madej 2021), which focused on the study of erosion and sedimentation in the Redwood Creek watershed, summarizes this body of work.

Unfortunately, much of the data from these studies remains buried in files and reports that are not publicly available (Wilzbach and Ozaki 2017). Using, Integrated Resource Management Applications (IRMA), however, park staff has begun to compile and make these studies available (see “Park-Specific Documents” in “Guidance for Resource Management”).

The value of the parks’ long-term data will only increase as time goes on. Such data are sentinels alerting investigators and land managers to trends in basic hydrological metrics (e.g., the response of rainfall or runoff to environmental change). Long-term data are meaningful because they provide a context for seasonal and annual variations as well as extreme events such as floods and droughts (fig. 5). These data are the crucial factual evidence for managing current and future provision of clean water supplies, predicting and mitigating the effects of floods, and protecting riverine ecosystems (Tetzlaff et al. 2017); they also may yield answers to questions that scientists did not even know to ask (Kuebbing et al. 2018).

The Redwood Creek watershed is one of the few sites in the United States with a long-term monitoring program of river channel responses to hillslope disturbances (Madej 2021). As a result, the parks have become a testing ground for large-scale forest and stream restoration of severely impacted lands (National Park Service 2019a).

The availability of long-term data puts managers at the parks in a prime position to monitor the effects of future changes in watershed condition and climate change (see “Climate Change”). Long-term monitoring also has put park managers in a position to assess the effectiveness of restoration activities (see “Restoration of Redwood Creek Watershed”) and provide guidance on land management policies to other agencies and landowners (Madej 2021).

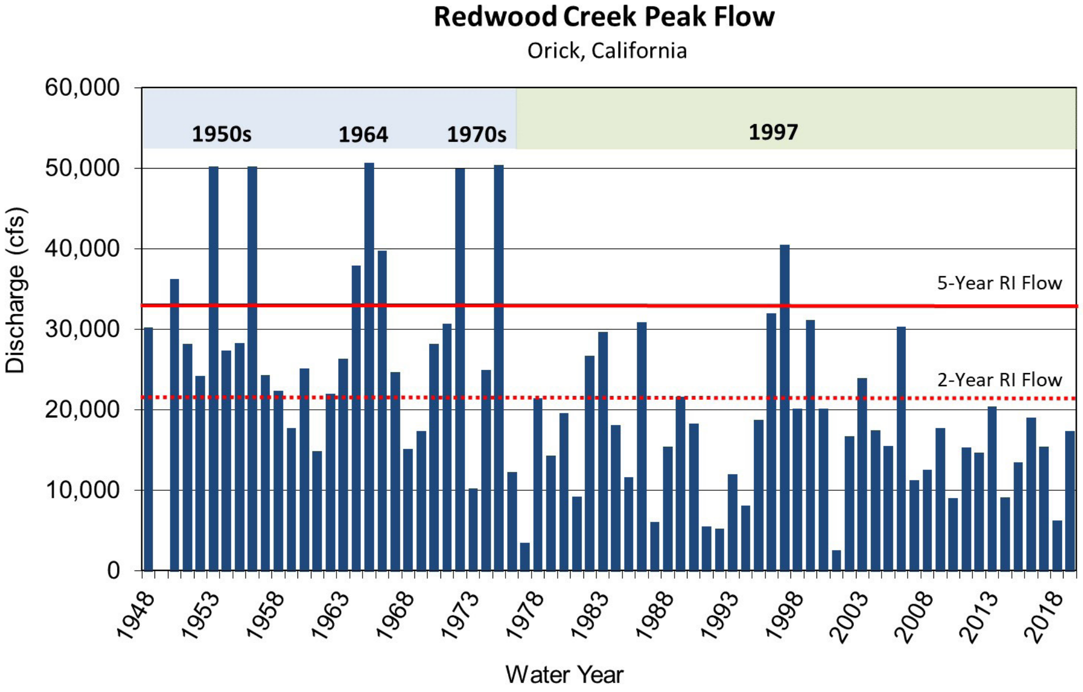

Figure 5. Graph of peak flow on Redwood Creek.
The graph shows a period of large flow events during the late 1940s to mid-1970s followed by much lower peak flows. Except for a storm event in 1997, which was a 10-year storm, all peak flow events have a return interval (RI) of less than a five-year event. These data provide the hydrologic framework to evaluate watershed and channel response to land use and storm events. NPS graphic courtesy of Vicki Ozaki (Redwood National and State Parks).

Redwoods: An Ancient Lineage

The "ancient redwoods" are a fundamental resource and value of the parks (National Park Service 2016a). "The ancestry of these trees goes back through millions of years, and their unbroken line of descent connects the present with the age of reptiles [i.e., Mesozoic Era or 251.9 million to 66 million years ago]. Their ancestors were the companions of the dinosaurs" (Shirley 1940, section 1).

Ongoing paleontological study verifies the ancestry of redwood trees (table 1). Indeed, the earliest known redwood fossils (*Sequoia jeholensis*) date back to the Middle to Late Jurassic Period (174.1 million to 145.0 million years ago) (Endo 1951; Zhang et al. 2015).

Table 1. Extant and extinct *Sequoia* species worldwide.

Source: Zhang et al. (2015), species with foliage only. Common names were provided by Justin Tweet (NPS Geologic Resources Division, paleontologist, email communications, 20 January and 31 March 2021). Notably, the coast redwood (*Sequoia sempervirens*) is the only extant species in the genus *Sequoia*. As the only living species, it is the only one with a widely used common name; generally, fossil species do not have common names, but (as shown in this table) approximations can be made using translations of the Latin names.

Species	Common Name	Age (Years Ago)	Distribution	References
Sequoia sempervirens	Coast redwood	Miocene (~23 million) to present	Worldwide to present-day range in California/Oregon	Watson and Eckenwalder (1993)
S. maguanesis	"of Maguan County, Yunnan, China" (the fossil locality)	Late Miocene (~11.63 million–5.3 million)	Southeast Yunan in southwest China	Zhang et al. (2015)
S. cf. sempervirens	cf = compare to	Miocene (23.0 million–5.3 million)	Northwest Yunan in southwest China	Ma et al. (2005)
S. affinis	"closely related to" or "akin to"	Paleocene to Pliocene (66.0 million–2.6 million)	North America	Chaney (1951); MacGinitie (1953); Meyer and Manchester (1997); Meyer (2003)
S. abietina	"like a fir tree" (firs being genus *Abies*)	Eocene to Miocene (56.0 million–5.3 million)	Europe (France, Switzerland, Poland, Czech Republic, Spain, Germany, Romania, Iceland)	Knobloch (1964); Kilpper (1968); Mai and Walther (1978); Barrón and Diéguez (2001); Grímsson et al. (2007); Worobiec et al. (2008)
S. chinensis	"of China" (although this is usually *sinensis*)	Late Cretaceous to Miocene (100.5 million–5.3 million)	Northeast China	Writing Group of Cenozoic Plants of China (1978); Ma et al. (2005)
S. lebedevii	In honor of someone with the last name "Lebedev"; a possible candidate is Russian paleobotanist E. L. Lebedev.	Late Cretaceous (100.5 million–66.0 million)	Russia (western Siberia)	Goloneva and Nosova (2012)
S. tenuifolia	"thin leaved" or "slender leaved"	Late Cretaceous	Russia (Franz Josef Land)	Sveshnikova and Budantsev (1969)
S. antiqua	"antique" (probably a reference to age or some feature considered to be primitive)	Late Cretaceous	Northeast Asia (Arkagalinskaya)	Samylina (1988)
S. microlepis	"small scale" (foliage shape and size?)	Late Cretaceous	Northeast Asia (Lena and Kolyma)	Sveshnikova (1967); Samylina (1988)
S. parvifolia	"small leaved"	Late Cretaceous	Northeast Asia (Lena River)	Samylina (1988)
S. jeholensis	"of Jehol," which may be the Jehol region or a specific city	Middle to Late Jurassic (174.1 million–145.0 million)	Northeast China	Endo (1951)
S. minuta	"very small" or "little," presumably referring to some feature	Early to Late Cretaceous (145 million–66.0 million)	Bohemia, Russia, China, North America	Sveshnikova (1967); Chen et al. (1988); Samylina (1988)

Diversification occurred during the Late Cretaceous Period (100.5 million to 66.0 million years ago) (Stewart and Rothwell 1993). The extant species, *Sequoia sempervirens*, dates to the Miocene Epoch (11.6 million to 3.6 million years ago) (Ozaki 1991).

Although referring to the coast redwood (*Sequoia sempervirens*) as a "living fossil" has dramatic appeal—for example in the parks' official film—this terminology is neither scientifically nor historically accurate. The dawn redwood (*Metasequoia glyptostroboides*), which is a close relative of the coast redwood, is more deserving of the title. In the 1940s, the discovery in south-central China of a living dawn redwood, which was thought to be extinct, attracted considerable attention and gained the moniker of "living fossil" (Chaney 1948a, 1948b).

The coast redwood flourished in Asia for many millennia before it migrated to the Western Hemisphere (Shirley 1940). Interestingly, this migration (i.e., exchange between East Asia and North America) took place across the Bering Land Bridge (see GRI report about Bering Land Bridge National Preserve by Lanik et al. 2019). The exchange of *S. sempervirens* via the Beringian Strait happened at a time, probably in the middle Miocene Epoch (approximately 14 million years ago), when the land bridge was not too cool for the spread of this thermophilic ("warmth-loving") conifer (Zhang et al. 2015).

During the Miocene Epoch, redwood forests existed in many parts of the world, including Japan, Russia, the United States (Montana and Nebraska), France, Germany, Poland, Azerbaijan, and Chile (Paleobiology Database 2019). Today, the sole surviving member of the *Sequoia* genus is the coast redwood (*Sequoia sempervirens*), which is restricted to a relatively narrow corridor along the Pacific Coast. The trees' range extends between two groves on the Chetco River in the southwest corner of Curry County, Oregon, to Salmon Creek Canyon in the Santa Lucia Mountains of southern Monterey County, California. This "redwood belt" is about 724 km (450 mi) long and generally 8 to 56 km (5 to 35 mi) wide (Roy 1965, 1966). Within this range, redwood trees grow or could grow on an estimated 647,500 ha (1.6 million ac; Olson et al. 1990). Of this area, about 23% is protected redwood forest and 77% is privately owned (Save the Redwoods League 2019).

The coast redwood has existed in its present range for some time, though probably not for 20 million years, as suggested on the NPS website (Redwood National and State Parks 2015). Fossil evidence of *S. sempervirens* in California includes material from La Brea Tar Pits (Los Angeles County), probably from the Late Pleistocene Epoch (126,000 to 11,700 years ago) (George and MacDonald 2017). Closer to the parks, Rocha et al. (1999) found evidence of a *S. sempervirens* forest that existed at the time of the Pliocene–Pleistocene boundary (2.6 million years ago) in the Fort Ord area of Monterey County. In 1997, storm waves uncovered exposures of the St. George Formation (**Tsg**; see GRI GIS data set) that host a late Miocene forest near Crescent City. The recovered fossil wood, however, is most likely western hemlock (*Tsuga heterophylla*; Robinson et al. 2001) not coast redwood.

Although a systematic investigation of the distribution of the genus *Sequoia* within the National Park System has not been conducted, NPS records show eight parks as hosting *Sequoia* fossils (table 2): (1) Katmai National Park and Preserve in Alaska (see GRI report by Hults and Fierstein 2016); (2) caves in Sequoia–Kings Canyon National Park in California; (3) Mojave National Preserve in California; (4) Florissant Fossil Beds National Monument in Colorado (fig. 6; see the GRI report by KellerLynn 2006); (5) John Day Fossil Beds National Monument in Oregon (see GRI report by Graham 2014); (6) the White Bird Battlefield (notable paleobotanical locality) in Nez Perce National Historical Park in Idaho; (7) the Santa Fe Trail (New Mexico portion); and (8) the Specimen Ridge or Fossil Forest (Amethyst Mountain) area in Wyoming of Yellowstone National Park (fig. 6) (Justin Tweet, NPS Geologic Resources Division, paleontologist, email communication, 9 August 2019).

Table 2. *Sequoia* fossils in the National Park System.

Source: Justin Tweet (NPS Geologic Resources Division, paleontologist, written and email communication, July 2020).

Park	Species	Formation	Age (Years Ago)	References
Florissant Fossil Beds National Monument	*Sequoia affinis*	Florissant Formation	Eocene (56.0 million–33.9 million)	Lesqueroux (1876); Peale (1907); Knowlton (1916)
John Day Fossil Beds National Monument	Sequoias (no information on species or genus)	John Day Formation	Miocene (23.0 million–5.3 million)	Justin Tweet (NPS Geologic Resources Division, paleontologist, email communication, 9 August 2019)
Katmai National Park and Preserve	*S. langsdorfii* *Note*: The name has been overapplied and used for specimens that belong to *Metasequoia*. Because of the taxonomic issues associated with the species, specimens assigned to it should be reevaluated.	Copper Lake Formation	Paleocene (possibly) to Eocene (66.0 million–33.9 million)	Hollick and Smith (1936)
Mojave National Preserve	*S. langsdorfii*	Unnamed rocks	Miocene (23.0 million–5.3 million)	Hazzard (1954)
Nez Perce National Historical Park	*Sequoia* (genus only, no species provided by Kirkham and Johnson [1929])	Latah Formation	Miocene (23.0 million–5.3 million)	Kirkham and Johnson (1929)
Santa Fe Trail	*S. gracilis* *Note*: Chaney (1951) considered this species much more like *Sequoiadendron*, which he interpreted as a subgenus of *Sequoia* but which now is considered distinct.	Whetstone Creek, New Mexico; formation unknown	Cretaceous (145.0 million–66.0 million)	Newberry (1898)
Sequoia–Kings Canyon National Park	*S. gigantea* *Note*: Santucci et al. (2001) did not specify a species; *S. gigantea* is actually *Sequoiadendron giganteus*, the giant redwood. Based on the geographic distribution of coast redwoods and giant redwoods, this probably is the giant redwood rather than *Sequoia*.	Within caves	The distribution of fossilized *Sequoia* in caves suggests that these trees existed in some areas of the park where they are not found today.	Santucci et al. (2001)
Yellowstone National Park	*S. magnifica*	Lamar River Formation	Eocene (56.0 million–33.9 million)	Knowlton (1899)

Figure 6. Photographs of fossil tree stumps.
Top: In Yellowstone National Park, a 50-million-year-old (Eocene) tree (*Sequoia magnifica*) stands on Specimen Ridge. This fossil tree is in the same genus as the living coast redwood (*Sequoia sempervirens*). Photograph by Katie KellerLynn (Colorado State University) taken in 2005. Bottom: Like the fossils in Yellowstone, *Sequoia affinis* at Florissant Fossil Beds National Monument also are from the Eocene Epoch. A group of three fossil stumps at the monument compose the distinctive "Redwood Trio." Imaging and modeling of the trio, which is susceptible to weathering, support monitoring and inventory efforts. NPS model (National Park Service 2021).

Geologic History, Features, and Processes

The geologic features and processes highlighted in this chapter are significant to the parks' landscape and history. Selection of these features and processes reflects input from scoping and conference-call participants, analysis of the GRI GIS data, and research of the scientific literature and NPS reports. These features and processes are discussed more-or-less in order of geologic age (oldest to youngest). A geologic time scale (table 3) shows the chronology of geologic events (bottom to top) that led to the parks' present-day landscape; this story covers about 200 million years.

The following geologic features and processes are discussed in this chapter:

- Plate Tectonic Context
- Josephine Ophiolite
- Franciscan Complex, including fossils
- Coast Range Thrust
- Grogan Fault Zone
- Coyote Peak Diatreme
- Wimer Formation, including fossils
- Prairie Creek Formation, including fossils
- Battery Formation and Marine Terraces, including Battery Formation fossils
- Fluvial Features and Processes, including modern streams (Smith River, Klamath River, and Redwood Creek) and stream processes that affect coast redwoods
- Coastal Features and Processes, including the parks' shoreline length, coastal slope stability, sea stacks, beaches and dunes, estuaries, lagoons, and tsunami deposits
- Intertidal Zone
- Offshore Geologic Features

Many of these features are rock formations that make up the parks' bedrock (fig. 7), which is commonly masked by dense vegetation. Bedrock is exposed along the coast in sea cliffs, sea stacks, and in the intertidal zone, however. Inland from the coast, stream channels, road cuts, and trail cuts may expose bedrock.

Table 3. Geologic time scale.

The geologic time scale puts the divisions of geologic time in stratigraphic order, with the oldest divisions at the bottom and the youngest at the top. The Quaternary Period and Tertiary time are part of the Cenozoic Era (the past 66 million years). The Triassic, Jurassic, and Cretaceous Periods are part of the Mesozoic Era (251.9 million to 145.0 million years ago). The periods from the Cambrian through Permian Periods are part of the Paleozoic Era (541.0 million to 251.9 million years ago). For a geologic history in chronological order, read the "Geologic Events" from bottom to top. GRI map unit symbols and abbreviations for each geologic time unit are in parentheses. Only geologic map units within the parks are included in the table; these are discussed in the text of the report. Ages in "Years Ago" reflect International Commission on Stratigraphy (2020), though some are specific dates provided by the source maps or other investigations (as cited).

Geologic Time Unit	Years Ago	Geologic Map Unit	Geologic Event	Park Locations
Quaternary Period (Q): Holocene Epoch (H)	Less than 3,500 (Abramson et al. 1998)	Tsunami deposits *Note*: This is not a unit in the GRI GIS data.	Six major tsunamis (as large or greater than the 1964 tsunami associated with the 9.2-magnitude Alaska earthquake) leave a record in sediments at Lagoon Creek and other coastal freshwater marshes.	Lagoon Creek
Quaternary Period (Q): Holocene Epoch (H)	Less than 4,200 (Delattre and Rosinski 2012)	Active channel: ● stream channel deposits, younger (**Qhc**) ● stream channel deposits (**Qscu**)	Sediments accumulate in active stream channels.	● Klamath River ● Smith River ● Redwood Creek

Table 3, continued. Geologic time scale.

Geologic Time Unit	Years Ago	Geologic Map Unit	Geologic Event	Park Locations
Quaternary Period (Q): Holocene Epoch (H)	Less than 11,700	Floodplain: ● young stream terrace deposits (**Qht**) ● stream channel deposits (**Qsc4** and **Qscu**)	Modern floodplains and stream channels develop.	● Klamath River ● Smith River ● Redwood Creek
Quaternary Period (Q): Holocene Epoch (H)	Less than 11,700	Beach sand (**Qbs**) Dune sand (**Qds**)	Unconsolidated marine-laid deposits form beaches and dunes along the coast. The source of this material is rivers. Beach sand migrates seasonally, forming spits at river mouths. Lagoons form as spits separate drowned mouths of stream valleys from the sea.	● Gold Bluffs Beach ● False Klamath Cove ● South of the mouth of the Klamath River ● Redwood Creek estuary
Quaternary Period (Q): Holocene Epoch (H)	Less than 11,700	Undifferentiated alluvium: ● young alluvial deposits, undifferentiated (**Qha**) ● alluvial deposits, undifferentiated (**Qa**)	Alluvial fans form at the mouths of tributaries. In addition, unconsolidated, poorly to moderately sorted sand, silt, and gravel form smooth geomorphic surfaces with little to no dissection.	● Klamath River ● Smith River ● Redwood Creek
Quaternary Period (Q): Pleistocene (PE) to Holocene (H) Epochs	Less than 2.6 million	Alluvial fan (commonly at the mouth of tributary canyons): ● young alluvial fan deposits (**Qhf**) ● alluvial fan deposits (**Qf**)	Alluvial fans record the activity of tributary streams. *Note*: Qf mapped in Redwood Creek watershed is Holocene (less than 11,700 years old). Qf mapped elsewhere in the parks is Pleistocene and Holocene (less than 2.6 million years old).	● Prairie Creek ● Hunter Creek ● Drainages above False Klamath Cove ● Mouth of Arthur Creek in the Redwood Creek watershed
Quaternary Period (Q): Holocene (H) and Pleistocene (PE) Epochs	2.6 million –~8,200 (Delattre and Rosinski 2012)	Terrace (former floodplain): ● stream terrace deposits (**Qt**) ● undifferentiated river terrace deposits (**Qrt**)	Rivers and tributary streams flow across the landscape. Incision and uplift go hand in hand. Terraces record the evolution of rivers.	● Redwood Creek watershed ● Mill Creek
Quaternary Period (Q): Late Pleistocene Epoch (PE)	126,000–11,700 *Note*: Abrasion platforms dated at approximately 125,000 or more; 105,000; and 80,000 (Polenz and Kelsey 1999).	Battery Formation (**Qby**)	**Qby** consists of marine terrace deposits (sand, clay, and gravel) with interfingering dune sands and alluvial gravels. **Qby** forms at or below sea level chiefly by wave abrasion but is now a step-like landform above sea level.	● Crescent City (north of the parks) ● Crescent Beach (at the north end of the parks)

Table 3, continued. Geologic time scale.

Geologic Time Unit	Years Ago	Geologic Map Unit	Geologic Event	Park Locations
Quaternary Period (Q): Late Pleistocene Epoch (PE)	More than 200,000–64,000 (Delattre and Rosinski 2012)	Marine terrace deposits (**Qmt**)	During times of stable sea level, waves cut platforms into the shore, which then rise with the land surface, creating marine terraces.	• Four remnants south of the mouth of the Klamath River • Inland from Freshwater, Stone, and Big Lagoons
Quaternary Period (Q): Holocene (H) and Pleistocene (PE) Epochs	Less than 2.6 million	Older terrace: Undifferentiated continental and marine deposits (**Qort**)	Erosion of the Redwood Creek watershed begins no earlier than 2 million years ago. The entire basin may be a Pleistocene landform (Cashman et al. 1995). Downcutting by Redwood Creek produces stream terraces that are subsequently uplifted.	Redwood Creek watershed
Quaternary Period (Q): Pleistocene Epoch (PE) to "historical" (including present-day activity)	Less than 2.6 million	Landslide deposits (**Qls**) *Note*: **Qls** is part of the geology GRI GIS data set. See geohazards GRI GIS data set for landslides and other types of slope movements in the Redwood Creek watershed.	Landslides become a common occurrence on the landscape.	In the northern part of the parks, **Qls** is associated with mélange unit of Crescent City area (**KJfmc**) and broken formation (**KJfbf**), including Last Chance Grade (see "Landslides"). At the south end of the parks, **Qls** is associated with the Redwood Creek schist (**KJfrc**). In the Redwood Creek watershed, landsliding is associated with the Redwood Creek schist and the incoherent unit of Coyote Creek (**KJfc**).
Quaternary Period (Q): Pleistocene Epoch (PE)	2.6 million –11,700	Terrace gravels of Surpur Creek (**Qsc**).	Rivers (e.g., the ancestral Klamath River) deposit thick layers of gravel in valleys. The gravels nearly bury hills in some locations.	Inland of the coast, north of Gold Bluffs Beach
Quaternary Period (Q): Pleistocene Epoch (PE)	Less than 4 million (Dell'Osso et al. 2002a)	n/a	The stream network in the Redwood Creek watershed forms sometime after deposition and uplift of the Prairie Creek Formation (**QTpc**).	n/a

Table 3, continued. Geologic time scale.

Geologic Time Unit	Years Ago	Geologic Map Unit	Geologic Event	Park Locations
Quaternary Period (Q) and Tertiary (T): Late Pliocene (PL) to early Pleistocene (PE) Epochs	About 3.6 million –781,000 *Note*: Dell'Osso et al. (2002a) suggested 4 million–1 million. The youngest deposits are no more than 700,000 years old (Bradley and Griggs 1976; Kelsey and Trexler 1989).	Prairie Creek Formation (**QTpc**).	An ancient Klamath River progrades (builds upward and outward) onto the continental shelf. Today, the Gold Bluffs represent this ancient mouth of the Klamath River. Following deposition of sediments, the Gold Bluffs were subsequently uplifted and dissected to form the present-day setting. The mouth of the Klamath River shifts north.	Gold Bluffs
Quaternary Period (Q) and Tertiary (T): Pleistocene (PE) and Pliocene (PL) Epochs	Before about 4 million (Dell'Osso et al. 2002a)	Undifferentiated continental and marine deposits (**QTg**)	Sediments record a gradual change from marine to lagoon to fluvial conditions.	On the eastern boundary of the parks, east of the mouth of Redwood Creek
Tertiary (T): Miocene Epoch (MI)	10 million –5 million (Aalto 2006) *Note*: Slightly older than QTpc	Wimer Formation (**Twi**)	Uplift of the Klamath Mountains uniformly raises the Klamath peneplain and overlying **Twi** sediments above sea level. Erosion removes much of the surface material, but some remnants (flat-topped ridges topped by the Wimer Formation) are preserved.	Jedediah Smith Redwoods State Park
Tertiary (T): Miocene Epoch (MI)	About 5 million (Stone 1992)	"Future" Wimer Formation	Marine sediments accumulate on the western margin of the Klamath peneplain in response to sea level rise. Sediments accumulate in an elongate basin referred to as the "Humboldt" or "Eel River" basin by Stone (1992). These sediments will become the Wimer Formation (**Twi**).	n/a
Tertiary (T): Miocene Epoch (MI)	About 10 million –5 million (Aalto 2006)	n/a	The Klamath peneplain of Diller (1902) forms as a regional, lowland erosion surface.	Within and east of Jedediah Smith Redwoods State Park
Tertiary (T): Miocene Epoch (MI)	11.6 million –3.6 million (Watson and Eckenwalder 1993)	n/a	First appearance of coast redwood (*Sequoia sempervirens*)	n/a
Tertiary (T): Miocene Epoch (MI)	About 14 million (Ozaki 1991)	n/a	Redwoods migrate from Asia to North America via the Bering Land Bridge.	n/a

Table 3, continued. Geologic time scale.

Geologic Time Unit	Years Ago	Geologic Map Unit	Geologic Event	Park Locations
Tertiary (T): Oligocene Epoch (OL)	About 28 million (Fritsche and Weigand 2008)	n/a	The East Pacific rise (spreading center between the Farallon plate and Pacific plate) makes contact with the western margin of the North American plate. As a result, the Mendocino triple junction forms, and the Farallon plate divides into smaller plates, including the Juan de Fuca and Gorda.	Off the coast of Cape Mendocino (south of the parks)
Tertiary (T): Paleogene Period (PG)	66 million –29 million (Morgan et al. 1985)	Coyote Peak diatreme (Ti)	On its way to the surface, a diatreme (breccia-filled volcanic pipe) intrudes the Franciscan Complex incoherent unit of Coyote Creek (**KJfc**) and the Redwood Creek schist (**KJfrc**) and pierces the North American plate.	Coyote Peak and a hill southwest of Coyote Peak (see poster)
Cretaceous Period (K)	100.5 million –66.0 million (Stewart and Rothwell 1993)	n/a	Diversification of redwood trees (see table 1)	n/a
Cretaceous (K) and Jurassic (J) Periods	163.5 million –66.0 million	Franciscan Complex, eastern belt (see Irwin 1964 for a description of "belts"): • metagraywacke (**KJfmg**) [metamorphosed sandstone] • broken formation (**KJfbf**) [graywacke (hard, dense, dark gray) sandstone] • mélange unit of Crescent City area (**KJfmc**). Includes individual blocks of greenstone (**KJfmcgs**), metagraywacke (**KJfmcmg**), radiolarian chert (**KJfmcch**), and undifferentiated rock masses (**KJfmcu**).	Marine sediments accumulate in a deep offshore submarine trench (associated with a subduction zone). In addition to ocean crust (e.g., basalt) and radiolarian chert, sediments eroded from the North American plate accumulate in the trench. Some trench sediments are subducted enough to become slightly metamorphosed. These rocks will eventually be raised above sea level and form most of the parks' bedrock.	• **KJfmg**: along the Coast Range thrust, i.e., between the broken formation (**KJfbf**) and Josephine ophiolite in Jedediah Smith Redwoods State Park • **KJfbf**: northern part of the parks, along the coast and in Jedediah Smith Redwoods State Park • **KJfmc**: northern part of the parks, inland from the broken formation; along the coast between False Klamath Cove and the mouth of the Klamath River

Table 3, continued. Geologic time scale.

Geologic Time Unit	Years Ago	Geologic Map Unit	Geologic Event	Park Locations
Cretaceous (K) and Jurassic (J) Periods	163.5 million –66.0 million	Franciscan units of Harden and others (1982): • transitional rocks of the Grogan fault zone (**KJfg**) [metamorphosed mudstone and sandstone] • coherent unit of Lacks Creek (**KJfl**) [sandstone and mudstone] • incoherent unit of Coyote Creek (**KJfc**) [mélange] • Redwood Creek schist (**KJfrc**)	See description for the Franciscan Complex (above).	• **KJfg**: the length of the Redwood Creek watershed • **KJfl**: east side of the Redwood Creek watershed • **KJfc**: east side of the Redwood Creek watershed • **KJfrc**: west side of the Redwood Creek watershed and along the coast
Cretaceous (K) and Jurassic (J) Periods	163.5 million –66.0 million	n/a	Plate collision and subduction associated with accretion of the Franciscan Complex (including marine sediments and ocean crust) begins. This process is still ongoing along the Cascadia subduction zone (west of the parks), though accretion of the Franciscan Complex itself ended during the Late Cretaceous Period (100 million–66 million years ago) (Blake et al. 1967; Harden 1998).	The entire length of the parks
Jurassic Period (J)	174.1 million –145.0 million (Endo 1951)	n/a	Appearance of the first redwood trees (*Sequoia jeholensis*) in the geologic record (NE Asia)	n/a
Jurassic Period (J)	201.3 million –145.0 million	Josephine ophiolite of Harper (1980): • dike complex (**Jdc**) • gabbro (**Jgb**) • peridotite (**Jpd**) • serpentinite matrix mélange (**Jspm**)	Josephine ophiolite forms on the seafloor in a nascent subduction zone. Following formation, layers of oceanic crust peel off and plaster against the leading edge of the North American plate as it overrides and scrapes against the top of the Farallon plate.	Jedediah Smith Redwoods State Park and the Klamath Mountains to the east
Jurassic Period (J)	201.3 million –145.0 million	n/a	Collision between the Farallon and North American plates creates a subduction zone that forms along the western margin of North America.	The entire length of the parks

Table 3, continued. Geologic time scale.

Geologic Time Unit	Years Ago	Geologic Map Unit	Geologic Event	Park Locations
Jurassic Period (J)	201.3 million –145.0 million	n/a	Pangea breaks up. The North American and Eurasian continents, previously joined, rift apart; the rift becomes the Atlantic Ocean. The North American continent (on the North American plate) moves westward and collides with the Farallon plate (precursor of the Pacific plate).	n/a
Triassic Period (TR)	251.9 million –201.3 million	n/a	Pangaea intact	n/a
Paleozoic Era, including the following periods: • Permian (P) • Pennsylvanian (PN) • Mississippian (M) • Devonian (D) • Silurian (S) • Ordovician (O) • Cambrian (C)	358.9 million –251.9 million	n/a	The supercontinent Pangea assembles between 340 million and 300 million years ago.	n/a
Proterozoic Eon	2.5 billion –541 million	n/a	n/a	n/a
Archean Eon	4.0 billion –2.5 billion	n/a	Oldest known rocks form.	n/a
Hadean Eon	~4.6 billion –4.0 billion	n/a	Earth forms.	n/a

Plate Tectonic Context

Plate tectonics is the unifying theory of how Earth works. It provides the “big picture” for geology, supplying a context for why continents move, seafloors spread, mountains rise, volcanoes erupt, and earthquakes happen. The Coast Ranges, of which the parks are a part (see “Geologic Heritage”), have provided insights into the theory of plate tectonics, and the rocks (see “Josephine Ophiolite” and “Franciscan Complex”), which accumulated and deformed in an active tectonic setting, provided evidence for the theory.

Interestingly, from 2003–2018, a Plate Boundary Observatory (PBO) station within the parks (at Schoolhouse Peak; see poster) precisely measured deformation of Earth’s crust resulting from the constant motion of the Pacific and North American plates. The PBO program, which was funded by the National Science Foundation (NSF) in conjunction with the National Aeronautics and Space Administration (NASA), explored the four-dimensional structure (three-dimensional space plus time) of the North American continent. In October 2018, PBO was assimilated into a broader Network of the Americas (NOTA), along with networks in Mexico (TLALOCNet) and the Caribbean (COCONet), as part of the NSF’s Geodetic Facility for the Advancement of Geosciences (GAGE).

Figure 7. Map of major geologic features in the parks.
The poster provides greater detail. The report text discusses these features. Table 3 puts these features in a context of geologic time. Graphic by Trista Thornberry-Ehrlich (Colorado State University) based on a poster courtesy of Vicki Ozaki (Redwood National and State Parks). Base imagery is ArcGIS World Imagery.

The Mendocino triple junction is a prime example of plate tectonics (fig. 8). Triple junctions form where three tectonic plates meet. In the 56-plate system commonly used to describe Earth's current tectonics, 108 triple junctions occur (Cronin 2021). In the case of the Mendocino triple junction, one continental (North American) and two oceanic (Gorda and Pacific) plates meet off the coast of California near Cape Mendocino, which is about 160 km (100 mi) south of the parks. North of Cape Mendocino, the oceanic plate underlying the seafloor (Gorda plate) is subducting (diving beneath) the North American continental plate; farther north, the Juan de Fuca plate is subducting. South of the Mendocino triple junction, California is characterized by right-lateral strike-slip faults (movement is horizontal and to the right) associated with the San Andreas Fault system (see GRI reports about Golden Gate National Recreation Area by Port 2016 and Santa Monica Mountains National Recreation Area by KellerLynn 2016).

Subduction is another example of plate tectonics. Subduction has dominated the parks' tectonic setting since dinosaurs walked the Earth and the first redwoods (*Sequoia jeholensis*) appeared in the geologic record. The Jurassic and Cretaceous bedrock in the parks (see "Josephine Ophiolite" and "Franciscan Complex") formed where 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—which later divided into the Juan de Fuca and Gorda plates (fig. 8)—descended beneath the thicker, more buoyant North American plate (fig. 9).

The trench (surface expression) of the Cascadia subduction zone is about 56 km (35 mi) offshore from the parks; the Cascadia subduction zone dominates the parks' tectonic setting. Collision between the Gorda plate, which is diving eastward at a rate of approximately 2–4 cm (0.8–1.6 in) per year (Nilsen and Clarke 1987; Clarke 1992), and the North American plate has resulted in east–northeast compression (forces that decrease volume or shorten). Compression is reflected in faults and associated folds (bends in bedrock) that trend north to northwest throughout the region (see "Quaternary Faults and Earthquakes"). The Redwood Creek basin, which follows the trace of the Grogan fault zone (see "Grogan Fault Zone"), illustrates this compression. The long, narrow watershed—about 110 km (70 mi) long and 11 to 14 km (7 to 9 mi) wide—trends north–northwest.

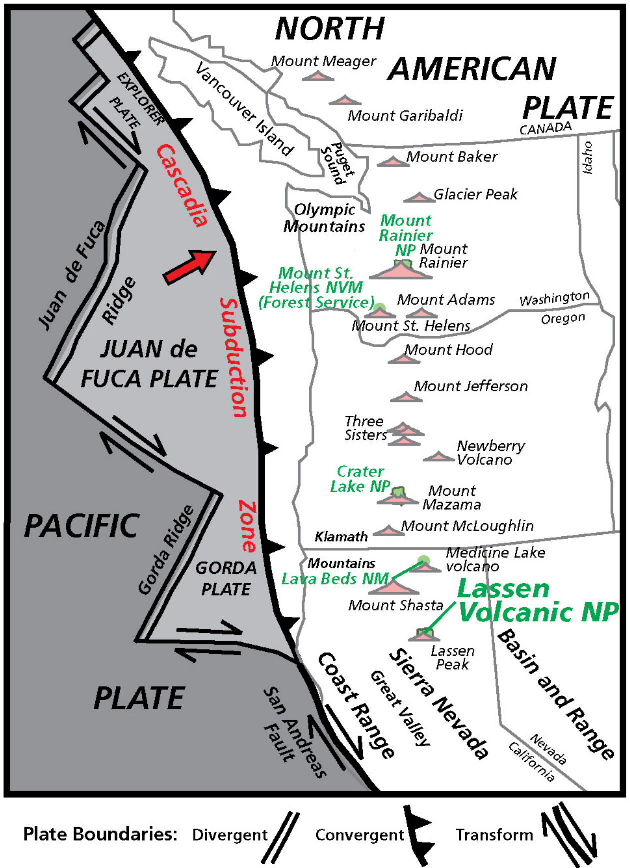

Figure 8. Illustration of plate boundaries along western North America.
The Mendocino triple junction (yellow star) and surrounding region represent a transition from convergent plate motion north of the triple junction to transform plate motion south of the triple junction. Convergent plate motion is associated with the Cascadia subduction zone. Transform plate motion associated with the San Andreas Fault system. To the west of the triple junction, the Gorda and Pacific plates slide past each other along the Mendocino fracture zone, which is a transform plate boundary. Volcanoes associated with the Cascadia subduction zone are noted on the graphic; no active volcanoes are associated with the Coast Ranges in California. Selected NPS areas are labeled. NPS graphic by Jason Kenworthy (NPS Geologic Resources Division) after Lillie (2005, figure 5.5).

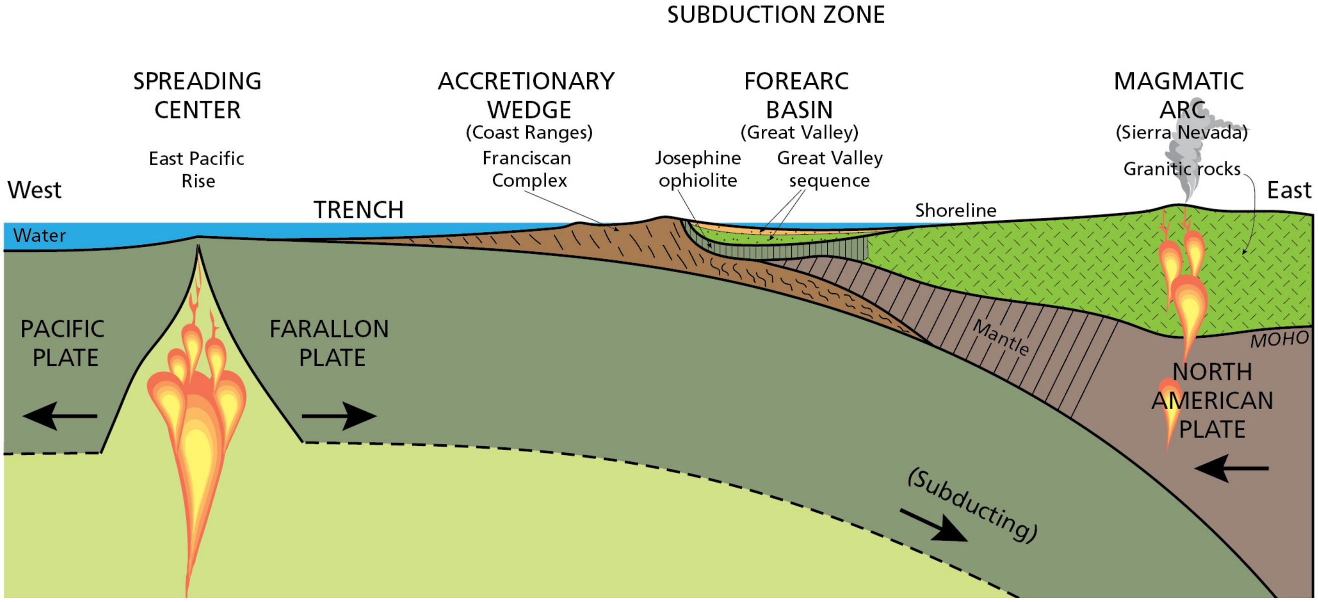

Figure 9. Generalized cross section of a subduction zone.
Before about 28 million years ago, the oceanic Farallon plate spread eastward from a spreading center/mid-ocean ridge, known as the East Pacific Rise, and subducted beneath the continental North American plate. The trench is the surface expression (on the seafloor) of subduction. From east to west, the subduction zone was composed of a magmatic arc (represented by granitic rocks of the Sierra Nevada), a forearc basin (represented by marine, sedimentary rocks of the Great Valley sequence), and an accretionary wedge (represented by the Franciscan Complex in the Coast Ranges). The Great Valley sequence was deposited on the Coast Range ophiolite (seafloor), which in the Klamath Mountains correlates with the Josephine ophiolite. Rocks associated with the accretionary wedge were jammed underneath and uplifted the ophiolite. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Crouch and Suppe (1993, figure 2) and Lillie (2005, figure 7.6).

Josephine Ophiolite

Map units: **Jspm**, **Jpd**, **Jgb**, and **Jdc**

Ophiolites are suites of mafic and ultramafic rocks, meaning they consist of igneous rocks (solidified from molten or partly molten material) with abundant dark-colored, iron- or magnesium-rich minerals. Originating on the seafloor, ophiolites, which are now on land, are a rare geologic treat (fig. 10). The appearance of the Josephine ophiolite ("**J**" map units) in the parks allows first-hand examination of rocks that are usually inaccessible. These rocks underlie the east side of Jedediah Smith Redwoods State Park (see fig. 2 and poster).

The ophiolite formed in a developing subduction zone about 164 million–162 million years ago (Harper et al. 1994). It was added to the North American continent via "accretionary uplift" (Shervais 2001) when the Franciscan Complex (see "Franciscan Complex") was jammed underneath it (see fig. 9).

Ophiolites can be as much as 5 km (3 mi) thick in the Klamath Mountains (Orr and Orr 1999), although an entire sequence is rarely preserved (Neuendorf et al. 2005). The Josephine ophiolite is one of the largest and most complete ophiolite sequences in the world (Orr and Orr 1999).

The map by Delattre and Rosinski (2012) divided the Josephine ophiolite into the following four units in the parks (see table 3):

- serpentinite matrix mélange (**Jspm**). Serpentinite is a metamorphic rock characterized by mottled shades of green and a resemblance to the skin of a serpent. Mélange is a body of jumbled rock that includes fragments and blocks of all sizes embedded in a fragmented and generally sheared matrix.
- peridotite (**Jpd**). Peridotite is a coarse-grained intrusive igneous rock composed primarily of olivine and other mafic minerals; it commonly alters to serpentinite.

- gabbro (**Jgb**). Gabbro is a group of dark-colored, coarse-grained intrusive igneous rocks.
- Dike complex (**Jdc**). A dike is a narrow igneous intrusion that cuts across bedding planes or other geologic structures).

Elsewhere, the Josephine ophiolite also contains sheared serpentinite (**Jsp**) above the mélange (**Jspm**), and cumulate (an igneous rock formed by accumulation of crystals that settle out from a magma by the action of gravity) ultramafic rocks (**Juc**) atop the peridotite (**Jpd**). The map by Dell'Osso et al. (2002a) combined these rocks and referred to them as "Klamath Mountain rocks, undifferentiated" (**Jk**).

Most of the rare plants in the parks grow on a substrate of Josephine ophiolite that occurs as a belt of ultramafic rocks stretching across northern Del Norte County (see fig. 2). Few nutrients are available for plant uptake in this belt because of the ultrabasic (high pH) chemistry and poor water-holding capacity of the soil that forms (Redwood National Park 1985). Bogs containing the carnivorous California pitcher plant (*Darlingtonia californica*) are associated with nutrient-poor serpentine soil and can be found in a handful of places in and adjacent to the parks near the Smith River (Vicki Ozaki, Redwood National and State Parks, geologist, written communication, 18 August 2020).

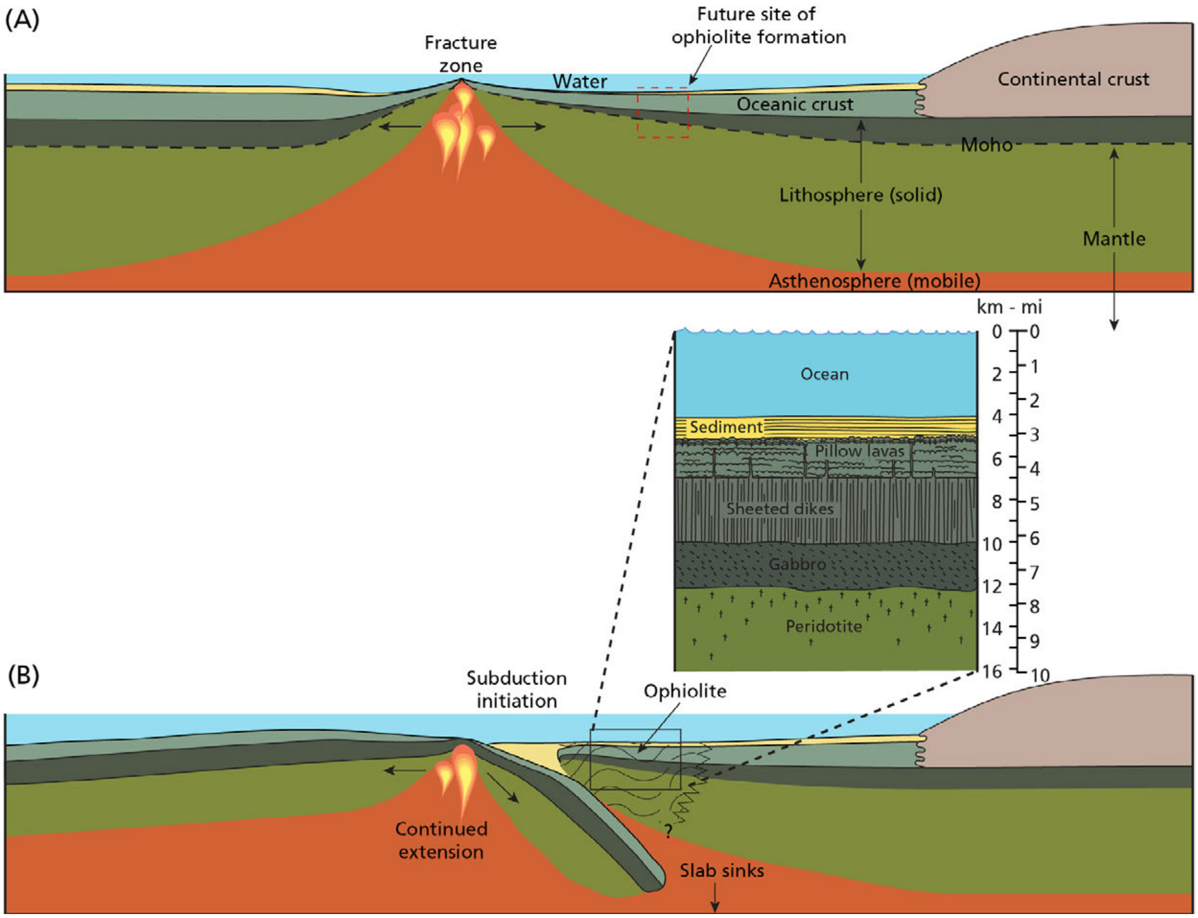

Figure 10. Schematic diagram of ophiolite formation.
(A) As a result of rifting and the initiation of subduction-related volcanism and plutonism, an ophiolite (suite of rocks that represents uplifted oceanic crust and upper mantle; see B inset) develops in a nascent or reconfigured subduction zone. "Moho" (short for Mohorovicic discontinuity) is the boundary between Earth's crust and mantle. (B) Melting of the subducting slab takes place, resulting in ophiolite formation. In a complete ophiolite sequence (bottom to top), sheared and serpentinized ultramafic rocks such as peridotite (e.g., map units Jspm and Jpd; see table 3), which formed in Earth's mantle, are overlain by accumulations of mafic igneous rocks, such as gabbro (e.g., Jgb), which formed at the base of ocean crust. These rocks, in turn, grade upward into sheeted dikes (e.g., Jdc), which represent volcanic activity along a zone of rifting and are the plumbing system for lava to get to the seafloor. Pillow lavas (composed of basalt) extruded onto the seafloor and lie atop the sheeted dikes. Deep marine sediment, such as chert, cap the sequence. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Strahler (1981, figure 10.28), Shervais (2001, figures 2 and 7), and Lillie (2005, figures 3.28 and 5.16).

Franciscan Complex

Map units: **KJfrc**, **KJfc**, **KJfl**, **KJfg**, **KJfmc**, **KJfbf**, and **KJfmg**

Named for San Francisco, the bedrock underlying most of the parks is composed of the Franciscan Complex (see fig. 7 and poster). The Franciscan Complex represents the accretionary prism that makes up the Coast Ranges (see fig. 9). The Franciscan Complex was accreted (tectonically emplaced) onto the western edge of the North American continent during a period of plate collision and subduction (e.g., Ernst 1983; McCrory 1989; Harden 1998). This wedge of material, which is more than 15,000 m (50,000 ft) thick (Oakeshott 1980), was scraped off the top of the subducting Farallon plate. It consists of former offshore sediments and fragments of ocean crust; some of the offshore sediments underwent metamorphism (in this case, low temperature and high pressure; Blake et al. 1967). Exposures of Franciscan rocks crop out along the parks' coast (see fig. 7) as well as in road cuts on the way to the Tall Trees Grove trailhead (see poster).

With respect to petrology (the branch of geology dealing with the origin, occurrence, structure, and history of rocks), the Franciscan Complex is a geologist's wildest dream. All three major classes of rocks—(1) igneous (rock solidified from molten or partly molten material), (2) sedimentary (rock derived from the consolidation of loose sediment), and (3) metamorphic (rock derived from preexisting rocks in response to changes in temperature, pressure, shearing stress, or chemical environment)—are represented in it. Moreover, the Franciscan Complex comprises seven units (see table 3) consisting of the following 12 rock types:

- chert—an extremely hard sedimentary rock with conchoidal (resembling a conch shell) fracturing, consisting mostly of interlocking crystals of quartz.
- conglomerate—a coarse-grained, generally unsorted, sedimentary rock consisting of cemented, rounded clasts larger than 2 mm (0.08 in) in diameter.
- graywacke—a dark gray, firmly indurated (hardened), coarse-grained sandstone that consists of poorly sorted angular to subangular grains of quartz and feldspar, with a variety of dark rock and mineral fragments embedded in a compact clayey matrix.
- metagraywacke (metamorphosed graywacke).
- mélange—In the circum-Pacific region (North America, New Zealand, and Japan), as well as the western Alps, the term "mélange" has been used to indicate chaotic rock bodies formed mainly by tectonic processes in a subduction zone. The association between mélange and subduction is closely linked in these regions (Cowan 1985) partly because the most popular chaotic rock bodies described (i.e., Franciscan Complex) have been mainly interpreted as a subduction product. Mélange, however, forms in other tectonic settings such as rifts ("pull-apart" basins in Earth's crust; Festa et al. 2010).
- mudstone—hardened mud having the texture and composition of shale but lacking its fissility (easily splitting along closely spaced planes).
- metamudstone (metamorphosed mudstone).
- metatuff—consolidated or cemented volcanic ash and lapilli (pyroclastic materials ranging between 2 and 64 mm [0.08 and 2.5 in] across with no characteristic shape) that has been metamorphosed.
- sandstone—clastic (made of fragments of preexisting rocks) sedimentary rock composed of predominantly sand-sized grains.
- metasandstone (metamorphosed sandstone).
- schist—a medium- to coarse-grained, strongly foliated, metamorphic rock with eminently visible mineral grains, particularly mica, which are arranged parallel to one another, imparting a distinctive sheen, or "schistosity," to the rock.
- serpentinite (see "Josephine Ophiolite" for an explanation).

Starting in 1895, repeated changes in nomenclature reflect the complexity of the rocks now referred to as the "Franciscan Complex." Lawson (1895) referred to them as an informal "series." Wilson (1943) referred to them as a "group" and Huey (1948) and Ogle (1953) as a "formation." Words such as "series," "group," and "formation" have particular meanings with respect to geologic nomenclature. For instance, in geologic terminology, a formation is the fundamental rock-stratigraphic unit. More than one formation may be combined to create a group. Bailey et al. (1964) avoided the problem of formal classification by referring to these rocks as "Franciscan rocks" and Brabb and Pampeyan (1972) by simply calling them "the Franciscan." Marvin and Dobson (1979) referred to these rocks as an "assemblage" as did Harden et al. (1982). Map authors Delattre and Rosinski (2012) used descriptions by Harden et al. (1982) but referred to these rocks as the Franciscan "Complex." Dott (1965) was the first to apply the term "complex" to these rocks. Wagner and Saucedo (1987) established usage of "complex" for these rocks in California on the regional geologic map of the Weed quadrangle (scale 1:250,000). A "complex" consists of rocks of two or more genetic classes (i.e., igneous, metamorphic, and sedimentary) with or without highly complicated structure (Neuendorf et al. 2005). The US Geologic Names Lexicon ("Geolex")—a national compilation of names and descriptions of geologic units maintained by the US Geological Survey (https://ngmdb.usgs.gov/Geolex/search; accessed 10 February 2021)—uses “Franciscan Complex” as the formal name for these rocks.

Fossils of the Franciscan Complex

The oldest known fossils from the parks are microscopic, single-celled organisms known as radiolarians. These organisms live primarily near the surface of the sea and make their skeletons of the mineral silica (SiO_2). After they die, their skeletons sink to the ocean floor. At the parks, they provide evidence for the origin of the marine environment of the Franciscan Complex.

Because the skeletons accumulate far from land, little other silicious sediment—only a bit of dust and volcanic ash—is added (Sloan 2006). Over time, the sediment hardens into radiolarian chert. Between layers of chert, dust and ash form thin layers of shale (a clastic sedimentary rock made of clay-sized particles and characterized by fissility).

Aalto et al. (1983) documented radiolarian microfossils in the green- and red-bedded radiolarian chert at the mouth of the Klamath River (fig. 11). North of there, a cliff face exposes notable outcrops. This radiolarian chert (**JKfmcch**) consists of blocks that are part of the mélange unit of Crescent City area (**KJfmc**). Investigators (Pessagno 1973, 1977; Aalto et al. 1983) used these fossils to date the chert as Late Jurassic (Tithonian Age, 152.1 million to 145.0 million years old).

Further evidence of the Franciscan Complex’s marine origin includes foraminifera, which, like radiolarians, are microscopic organisms that produce mineralized skeletons, though foraminifera tests (shells) are more commonly made of calcite ($CaCO_3$), rather than silica. Sliter (1984) described foraminifera from a Cretaceous limestone unit within the Franciscan Complex at the parks; these rocks are probably the mélange unit of Crescent City (**KJfmc**), which is the only Franciscan unit described by source map authors (Delattre and Rosinski 2012) as containing limestone.

In the Franciscan Complex mélange unit of Crescent City area (**KJfmc**) at Point Saint George (north of the parks), Miller (1997) described *Bathysiphon aaltoi*, which is an incredibly large foraminiferid (single-celled, marine organism) that was discovered by Richard Buckhart. Foraminiferid are typically microscopic, so at 124 mm (4.88 in) in length and 4 mm (0.2 in) in maximum diameter, the specimen described by Miller (1997) is phenomenal. Furthermore, the specimen consisted of an incomplete test. The original test may have exceeded 150 mm (5.9 in) in length, making it one of the largest foraminiferids ever discovered. Although determining the cell-body size of *B. aaltoi* is not possible, the overall size of their tests, suggests that the species may have produced some of the largest protistan (single) cells known (Miller 1997). Miller (1991, 1995) had previously described other large foraminiferid specimens.

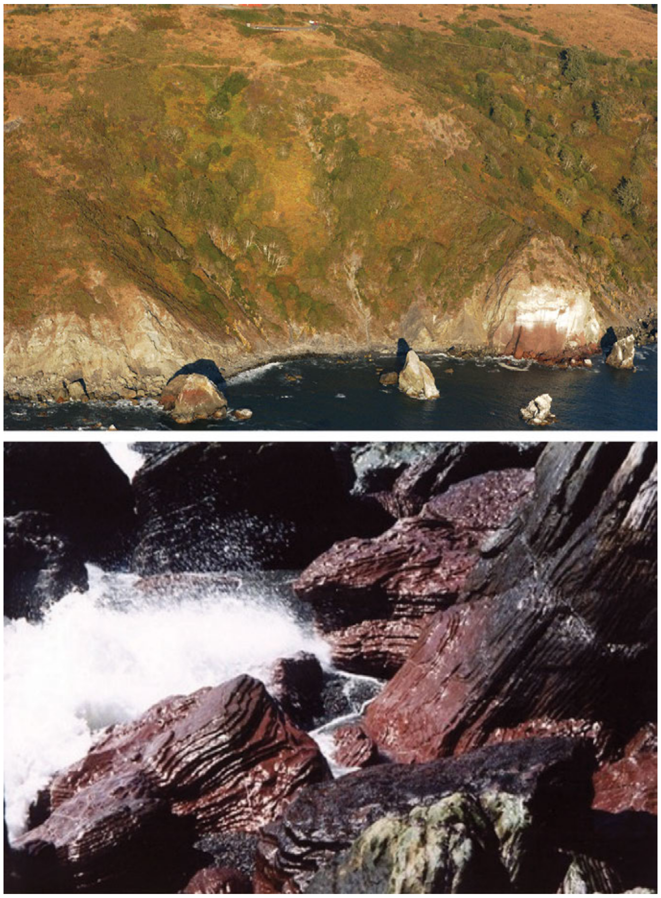

Figure 11. Photographs of radiolarian chert. Mélange units of the Franciscan Complex contain radiolarian chert, which is composed of microscopic, single-celled, marine animals. In the parks, outcrops of green- and red-banded radiolarian chert are found north and south of the mouth of the Klamath River. Top: Photograph (Image 7377, taken 13 October 2002) by California Coastal Records Project. Copyright © 2002–2021 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.californiacoastline.org, used by permission. Bottom: NPS photograph courtesy of Vicki Ozaki (Redwood National and State Parks), taken north of the mouth of the Klamath River, ca. 2000, photographer unknown.

In addition, the Franciscan Complex on the east side of the Redwood Creek watershed yielded two ammonites—*Desmoceras* (*Pseudouligella*) *japonicum* and *Calycoceras* sp. (Harden et al. 1982; Vicki Ozaki, Redwood National and State Parks, geologist, personal communication *in* Santucci and Kenworthy 2009, p. 53). Because of their beautiful shells—ribbed and spiraled—ammonites are a widely recognized fossil. The earliest ammonites appeared during the Devonian Period; the last species vanished, along with dinosaurs, in the Cretaceous–Tertiary (formally known as the Cretaceous–Paleogene) extinction event. The parks' two ammonites are from the Cretaceous Period (Cenomanian Age, 100.5 million to 93.9 million years old). Unfortunately, the map unit that contains these fossils is unknown. The most likely candidate is the mélange unit of Crescent City (**KJfmc**) because it contains limestone; however, this mélange unit was not mapped in the Redwood Creek watershed (see poster), where the ammonites are thought to have been discovered.

Coast Range Thrust

Associated map unit: **KJfmg**

The Coast Range thrust is a fault of regional extent that roughly forms the boundary between the Coast Ranges on the west and the Klamath Mountains on the east. It is readily apparent on geologic maps of the northern part of the parks (see figs. 2, 7, and poster).

Thrust faults slope like ramps. The rock above a thrust fault is pushed up and over the rock below. The Coast Range thrust fault is not presently undergoing active deformation, but during the Jurassic and Cretaceous Periods, thrust faulting put the Josephine ophiolite and Franciscan Complex in motion. As a present-day comparison, active thrust faulting is taking place along the Cascadia subduction zone (see "Quaternary Faults and Earthquakes"). At the parks, the Coast Range thrust marks where older rocks (i.e., Josephine ophiolite) of the Klamath Mountains were thrust westward over the younger Franciscan rocks of the Coast Ranges.

Looked at another way, the accretionary wedge of material (i.e., Franciscan Complex) underthrust or underpin the Klamath Mountain rocks (**Jk** of Dell'Osso et al. 2002a). The process of accretion resulted in progressive metamorphism in the Franciscan Complex, with metamorphism increasing closer to the thrust fault. Coincident with increasing metamorphism, rocks of the Franciscan Complex become more folded closer to the thrust fault. Near the thrust fault, the folds are so tight (squashed together) that their limbs (area of a fold between adjacent fold hinges) are parallel (Blake et al. 1967).

Three "textural zones" (1, 2, and 3), which Delattre and Rosinski (2012) noted in their descriptions for the Franciscan Complex, relate to progressive metamorphism; these textural zones were originally identified by Blake et al. (1967). The zones go from no metamorphism on the west to complete recrystallization on the east. Notably, Franciscan Complex mélanges are not associated with textural zones because they are not metamorphic rocks. In general, zone 1 contains unmetamorphosed rocks, such as Franciscan Complex broken formation (**KJfbf**; see fig. 7 and poster); these rocks show no evidence of bending, breaking, or crushing of minerals either in outcrop or under a hand lens (Blake et al. 1967). Rocks in zone 2, including Franciscan Complex metagraywacke (**KJfmg**), are found along the Coast Range thrust (see fig. 7 and poster) and show signs of bending, breaking, or crushing of minerals under a hand lens. Rocks in zone 3 are completely recrystallized to quartz-mica schist, which is characteristic of intense metamorphism; the mineral mica has perfect cleavage, readily splitting into thin sheets. "Pure" zone 3 rocks do not occur within the parks, but the Redwood Creek schist (**KJfrc**) is an example of a rock from transitional textural zone 2 and 3. Transitional types also exist between textural zones 1 and 2.

Grogan Fault Zone

Associated map unit: **KJfg**

Like the Coast Range thrust, the Grogan fault zone is a distinctive feature in the parks and clearly displayed on a geologic map (see fig. 7 and poster). In contrast to the Coast Range thrust, however, the Grogan fault zone is an active fault with a slip rate of 0.2–1.0 mm (0.008–0.04 in) per year (see "Quaternary Faults and Earthquakes").

The Grogan fault zone is parallel to the major geologic/tectonic structures of northern California (Strand 1962; Janda et al. 1975; Harden et al. 1982). As such, it trends north–northwest. The total length of the fault zone, including both onshore and offshore segments, is 154 km (96 mi). On land within the parks, it marks an imposing, linear canyon.

The Grogan fault zone has a strong influence on the parks' topography and geomorphology, particularly Redwood Creek and the Redwood Creek watershed. Redwood Creek follows the fault zone along 80% of its length (Vicki Ozaki, Redwood National and State Parks, geologist, written communication, 19 August 2020). As a consequence of compression along the fault zone, narrow ridges and valleys characterize the Redwood Creek watershed (Falls et al. 2003). Most tributaries are short, steep, and drain relatively small areas (Redwood National Park 1985).

The Grogan fault zone splits the Redwood Creek watershed, separating the Redwood Creek schist (**KJfrc**) on the west side from the incoherent unit of Coyote Creek (**KJfc**) and coherent unit of Lacks Creek (**KJfl**) on the east side (see fig. 7 and poster). All these rocks units are part of the Franciscan Complex. Transitional rocks of the Grogan fault zone (**KJfg**), which also are part of the Franciscan Complex, are associated with the fault zone and separate rocks on either side. The term "transitional" refers to the texture and degree of metamorphism of these rocks; that is, transitional rocks are intermediate in texture and degree of metamorphism between the metamorphosed Redwood Creek schist (**KJfrc**) on the west side of the basin and the unmetamorphosed mélange of the incoherent unit of Coyote Creek (**KJfc**) on the east. Transitional rocks of the Grogan fault zone belong to textural zone 2 of Blake et al. (1967).

North of the Redwood Creek watershed, the Grogan fault zone cuts through the Prairie Creek Formation (see "Prairie Creek Formation"). Movement along the fault has juxtaposed Pliocene and Pleistocene rocks and sediments (**QTpc**) against Jurassic and Cretaceous rocks (**KJfg** and **KJfl**) atop the Gold Bluffs in Prairie Creek Redwoods State Park. Like the fault zone itself, this juxtaposition is visible on a geologic map, for example, where the light-blue map unit of the transitional rocks of the Grogan fault zone (**KJfg**) are adjacent to the brown map unit of the Prairie Creek Formation **QTpc** (see poster).

Coyote Peak Diatreme

Map unit: **Ti**

A diatreme is a volcanic pipe formed by a gaseous explosion; it is filled with breccia (coarse-grained, generally unsorted sedimentary rock consisting of cemented angular clasts). Dell'Osso et al. (2002a) mapped the Coyote Creek diatreme (**Ti**) in two areas at the southern end of the parks: one at Coyote Peak and the other southwest of Coyote Peak (see poster).

The Coyote Creek diatreme was emplaced near a converging plate margin where young, hot, mantle and crust of the oceanic Gorda plate (or Juan de Fuca plate) were probably subducting obliquely beneath a thin lip of the North American plate. The diatreme is thought to have intruded the Franciscan Complex after the incoherent unit of Coyote Creek (**KJfc**) was emplaced against North America (Falls et al. 2003). The diatreme also intruded the Franciscan Complex, Redwood Creek schist (**KJfrc**).

The Coyote Creek diatreme has a complex composition and rare minerals. Erd and Czamanske (1983) identified and described two previously unknown minerals (orickite and coyoteite; named for the town of Orick and Coyote Peak) from these rocks, and Evans and Clark (1981) identified and described bartonite (named in honor of Paul Booth Barton, Jr., an ore petrologist with the US Geological Survey). Due to the rarity of these minerals, study and analysis used only a few grains of each mineral found in a few specimens. These rare minerals are stored at the Smithsonian Institution, Museum of Natural History (Vicki Ozaki, Redwood National and State Parks, geologist, written communication, 18 August 2020). In addition, the diatreme contains inclusions of Franciscan sedimentary rocks and aphanitic (containing fine-grained mineral crystals not detectable by the unaided eye) alkalic (characterized by elevated concentrations of sodium and potassium) igneous rocks. The unusual chemistry may be the result of the complex tectonic setting, which also could have included local strike-slip ("horizonal" movement) and extensional (e.g., rifting) environments within the two plates pierced by the diatreme (Morgan et al. 1985).

Wimer Formation

Map unit: **Twi**

The Wimer Formation represents material that accumulated on a regional, low-relief erosion surface called the "Klamath peneplain." Diller (1902) was the first to interpret the existence of this peneplain from characteristic features in the Klamath Mountains, namely flattish or gently rounded summits all at approximately the same altitude. Subsequent investigators have continued to recognize the peneplain over a large area, including in the highlands east of Crescent City.

The Klamath peneplain (erosion surface) formed during the late Miocene Epoch but then became submerged because of sea level rise; whereupon "cover rocks" (sediments of the Wimer Formation) accumulated atop the submerged surface. The source of the sediment is probably local (Franciscan Complex), though another possible source is older, plutonic rocks (formed at great depth beneath Earth's surface) of the Idaho batholith (a large, plutonic body of rock having an areal extent of 100 km^2[40 mi^2] or more and no known floor) in the western part of California (Aalto et al. 1998).

The Wimer Formation has two facies (depositional environments reflected in the features of a sedimentary rock): (1) western estuarine marine facies and (2) eastern fluvial (river) facies (Stone 1992). Each has a characteristic set of properties such as color, mineral constituents, grain size, and sedimentary structures representative of its origins. The two facies are correlated because they are next to each other and occupy the same geomorphic surface (i.e., the Klamath peneplain).

Following deposition of the Wimer Formation, movement along the Del Norte fault, which runs between the northern portion of Jedediah Smith Redwoods State Park and Lake Earl State Wildlife Area (see poster), uplifted and tilted the Klamath peneplain surface during the Late Pleistocene Epoch (Stone 1992; Aalto 2006). Likewise, the shoreline shifted eastward approximately 10 km (6 mi) (Watkins 1974; Stone 1993), causing erosional stripping of sediments from the peneplain.

Today, uplifted remnants—as high as 550 m (1,800 ft) above sea level—of the northeastern portion of the Klamath peneplain are exposed near Crescent City and the Smith River. The deposits consist of the estuarine and fluvial facies of the Wimer Formation as well as the nearshore St. George Formation (**Tsg**; see geology GRI GIS data set) at Point Saint George (not within the parks). Within the parks, the Wimer Formation (**Twi**) is discontinuous but found on the Franciscan Complex and Josephine ophiolite on both sides of the Coast Range thrust (see poster).

Fossils of the Wimer Formation

Siltstone (a sedimentary rock composed of silt-sized grains [intermediate in size between fine-grained sand and coarse clay]) of the western estuarine facies of the Wimer Formation is highly bioturbated (mixed and churned by organisms) and contains molluscan fauna (Stone 1992). Watkins (1974) conducted a paleobiological study of fossil molluscan communities of the Wimer Formation and defined two communities: First, a *Cryptomya californica* community is characterized by the coexistence of *Cryptomya californica*, *Macoma nasuta*, and a berbardinid bivalve. This community is found in the Bald Hills area of the parks. The *Cryptomya californica* community indicates a protected coastal mudflat environment of intertidal or very shallow subtidal depth. Second, the *Macoma balthica* community is typified by *Macoma balthica* and *Mya arenaria* and is found east of the Bald Hills outside of the parks. The landward *Macoma balthica* community may represent brackish conditions (Watkins 1974).

In addition, Watkins (1974) reported that the Wimer Formation contains fossils of marine diatoms (microscopic, single-celled algae) and angiosperm (flowering plant) leaves. Diatoms described by Stone (1992) came from the Bald Hills area.

Prairie Creek Formation

Map unit: **QTpc**

The Prairie Creek Formation (**QTpc**) represents the ancestral mouth of the Klamath River (Kelsey and Trexler 1989; Falls et al. 2003). Since about 700,000 years ago (i.e., deposition of the Prairie Creek Formation; see table 3), the mouth of the river has shifted north. The current mouth is 12 km (8 mi) north of this ancestral location.

Indicative of the formation's origin, sediments of the Prairie Creek Formation (weakly consolidated sand and gravel, grading upward from sand to coarse sand and gravel) reflect a variety of deposition settings, including river, nearshore marine, delta, estuary, and beach (Cashman et al. 1995). The best exposures of the Prairie Creek Formation are along the coastal bluffs at Gold Bluffs Beach (see fig. 7 and poster). At this location, thickness of the formation exceeds 550 m (1,800 ft), providing a stunning backdrop for visitors.

The Grogan fault zone, Lost Man fault, and unnamed faults cut the Prairie Creek Formation (see poster). Quaternary activity on these faults has progressively uplifted the Prairie Creek Formation on the east by as much as 300 m (900 ft; Cashman et al. 1995).

Named for exposures along Prairie Creek, the Prairie Creek Formation overlies the Franciscan Complex with an angular unconformity (significant disruption in the deposition of sedimentary strata). In an angular unconformity, the underlying strata are tilted at a different angle than the overlying strata. The unconformity between the Franciscan Complex and Prairie Creek Formation represents a "gap" in the rock record of at least 62 million years between the Cretaceous Period and Pliocene Epoch (see table 3).

The dominant source rocks of the Prairie Creek Formation are plutonic and metamorphic rocks from the Klamath Mountains to the east of the parks (Kelsey and Trexler 1989; Cashman et al. 1995). Uranium (U)–lead (Pb) ages of individual zircon grains in sediments of the Prairie Creek Formation revealed a previously unrealized provenance—the Idaho batholith (Michalak et al. 2016). Thus, while the ancestral Klamath River was actively depositing the sands and gravels of the Prairie Creek Formation, other large ancestral rivers were delivering sediment all the way from Idaho. This discovery has serious implications for interpreting the regional development of river systems of the northwestern United States (Michalak et al. 2016). The Prairie Creek Formation contains only minor amounts of Franciscan Complex detritus, mainly near the bottom of the exposed section (exposed surface or cut through Earth's surface) (Cashman et al. 1995).

Fossils of the Prairie Creek Formation

A single mollusk fossil (*Protothaca hannibali*) provides a general age of 4 million to 1 million years old for the Prairie Creek Formation. This specimen was discovered at the base of the formation (Kelsey and Trexler 1989; Cashman et al. 1995; Falls et al. 2003). An upper limit on the age of the formation is unknown, though a proposed minimum age is based on correlation to Late Pleistocene (less than 700,000 years old) marine terraces (wave-cut platforms) along the California coast (Bradley and Griggs 1976; Kelsey and Trexler 1989). As such, the youngest deposits of the Prairie Creek Formation, which are partly preserved as a tilted marine terrace, are no older than 700,000 years.

Reflecting its origin at the mouth of the ancestral Klamath River, the Prairie Creek Formation has a variety of fossils, including two species of freshwater pelecypods (*Mytilus* sp. and *Macoma* sp.), burrows, radiolarians, and a portion of a possible vertebrate rib (Criswell 1968; Moore and Silver 1968; Harden et al. 1982; Kelsey and Trexler 1989).

The Prairie Creek Formation also has abundant plant fossils such as peat-like deposits, leaf impressions, carbonized leaves, cones, and logs. Carbonized logs from the formation range in size from less than 3 cm (1 in) to more than 60 cm (2 ft) in diameter (Moore and Silver 1968). The Gold Bluffs yielded 18 species of plants (Criswell 1968); of these, 50% were trees, 37% were shrubs, and 13% were herbs. Kelsey and Trexler (1989) noted buried trees in growth position in the Gold Bluffs; these fossils are indicative of a stable floodplain of the ancestral Klamath River. None of these plant fossils are clearly identified as coast redwood (*Sequoia sempervirens*), however (see "Redwoods: An Ancient Lineage").

In the 1970s (before expansion of the national park), Sam Morrison, who was one of the original USGS mappers of the Redwood Creek watershed, collected petrified wood from the Prairie Creek Formation with the intention of identifying the wood and determining the paleoecology of the ancestral Klamath River. This study did not take place, however (Vicki Ozaki, Redwood National and State Parks, geologist, personal communication, 8 October 2019), and potential for future study, perhaps by a Scientists in Parks (SIP) participant (see "Guidance for Resource Management") remains. The collected fossils are retained by Sam Morrison in a box in his garage (Vicki Ozaki, Redwood National and State Parks, geologist, written communication, 18 August 2020).

Battery Formation and Marine Terraces

Map units: **Qby** and **Qmt**

The Battery Formation (**Qby**) is named from exposures at Battery Point (Maxson 1933), which is located on the south side of Crescent City. The formation is exposed in and around Crescent City and extends southward along Crescent Beach into the parks (see fig. 7 and poster).

The Battery Formation makes up much of the Crescent City coastal plain (flat, low-lying land area next to the ocean). At Battery Point, the Battery Formation is unconsolidated to consolidated marine sand, 3 to 5 m (10 to 16 ft) thick. The overlying sediments locally exceed 20 m (70 ft) thick (Polenz and Kelsey 1999) and may include younger (Holocene) beach deposits (**Qbs**), dune sand (**Qds**), young alluvial deposits (**Qha**), and estuarine deposits (**Qe**; mapped in Crescent City, not the parks; see geology GRI GIS data set).

Starting with its formal naming in 1933, the Battery Formation has been identified as a marine terrace (a geomorphic term describing a relatively level or gently inclined benchlike landform that initially formed by wave abrasion at or below sea level but is now above sea level). Following formation, the platform and related sedimentary covering of the Battery Formation were uplifted. Uplift rates for the Crescent City coastal plain are as much as 30 cm (10 in) per 1,000 years (Polenz and Kelsey 1999).

Based on work by Polenz and Kelsey (1999), the source map by Delattre and Rosinski (2012) includes three marine terrace levels as part of the Battery Formation; these terraces represent high stands of sea level at 125,000 or more years ago, 105,000 years ago, and 80,000 years ago. Marine terraces associated with these sea-level high stands are common along the Pacific coast (Muhs et al. 1992). Elsewhere in the National Park System (see, e.g., the GRI report about Cabrillo National Monument by KellerLynn 2018), the Bird Rock and Nestor terraces represent the 125,000-year-old and 80,000-year-old platforms, respectively.

Compared to distinctive flights of terraces in southern Oregon and near Cape Mendocino, the terraces at Crescent City are much less pronounced (Polenz and Kelsey 1999). Within the parks, the marine terrace deposits (**Qmt**) at Gold Bluffs Beach are more pronounced than those at Crescent City. South of the parks, as many as six marine terrace levels (**Qmt6**–**Qmt1**) are found near Patrick's Point State Park and Trinidad (see poster). The oldest of these is the Maple Stump terrace (**Qmt6**), which formed 200,000 or more years ago; the youngest of these is the Patrick's Point terrace (**Qmt1**), which formed about 64,000 years ago

(Delattre and Rosinski 2012). None of the marine terraces (**Qmt**) in the parks are numbered (see poster).

Fossils of the Battery Formation

Based on the fossils it contains and amino acid racemization dating of a clam fossil (*Saxidomus giganteus* Deshayes), the Battery Formation is Late Pleistocene (approximately 100,000 years old) (Addicott 1963; Wehmiller et al. 1977; Kennedy et al. 1982). The formation was likely deposited during the most recent Pleistocene interglaciation (warm period), referred to as the Sangamon, when sea level was somewhat higher than it is now (Moore and Silver 1968).

Fluvial Features and Processes

Map units: **Qsc** ("sc" for Surpur Creek), **Qort**, **Qrt**, **Qt**, **Qf**, **Qhf**, **Qa**, **Qha**, **Qht**, **Qsc4** ("sc" for stream channel), **Qscu** ("sc" for stream channel), and **Qhc**

As discussed in "Fossils of the Prairie Creek Formation," fluvial processes have been active on the landscape for at least 700,000 years and possibly for as long as 4 million years. The late Pliocene to early Pleistocene Prairie Creek Formation (**QTpc**) predates the modern fluvial systems at the parks. In addition, Pleistocene terrace gravels of Surpur Creek (**Qsc**), which is an informal unit of the Prairie Creek Formation mapped by Kelsey and Trexler (1989) and included in the GRI GIS data, predate modern stream activity.

In geologic interpretations, "modern" generally refers to landforms and landscapes that have formed since the Ice Age, which is commonly associated with the Pleistocene Epoch (2.6 million–11,700 years ago). In the case of the parks' landscape, however, many present-day landforms started forming earlier than 11,700 years ago. Modern stream channels, for example, began to form in the Pleistocene Epoch and continued to evolve in the Holocene Epoch.

Based on mapping of alluvial fans (**Qf**) by Delattre and Rosinski (2012), development of tributary channels also began in the Pleistocene Epoch. Mapping of alluvial fans (**Qf**) by Dell'Osso et al. (2002a) shows tributary development to have begun more recently, that is, in the Holocene Epoch. This difference may represent development of the Klamath River (older), which was documented by mapping of Delattre and Rosinski (2012), compared to Redwood Creek (more recent), which was documented by mapping of Dell'Osso et al. (2002a).

River terraces (**Qort**, **Qrt**, and **Qt**)—which occur as platforms (raised surfaces) above the active channel and floodplain—represent former, now-abandoned floodplains. Fluvial terraces record the evolution of river valleys. Multiple terraces indicate that incision of a valley was not steady (Connell et al. 2005). Relative to other terraces in a sequence, the higher a terrace above the modern channel, the older it is. As such, terraces record downward incision of a river through time. Regarding map unit names, Dell'Osso et al. (2002a) used "river" terrace (**Qrt**) whereas Delattre and Rosinski (2012) used "stream" terrace (**Qt**); the word choice, however, does not seem to have a particular geomorphic or geologic-age significance. Both sets of source map authors used "stream" for all younger units (see table 3).

The Tall Trees Grove on the west side of Redwood Creek is an excellent place to observe the development of a stream valley as preserved by a suite of terraces: two terraces rise above the modern channel at the Tall Trees Grove (fig. 12). Farther south along the Tall Trees Trail, three terrace levels are preserved. Rounded pebbles and cobbles, indicative of fluvial activity, are exposed in trail cuts (Vicki Ozaki, Redwood National and State Parks, geologist, written communication, 19 August 2020).

Regional uplift is a factor in the amount of river incision and terrace development that take place along a stream channel. In general, greater uplift equates to greater incision and more terrace development. Studies of marine terraces (see "Battery Formation and Marine Terraces") have calculated uplift rates of the Crescent City platform, as well as rates associated with the Cascadia subduction zone, at 0.45–1.08 m (1.5–3.54 ft) per 1,000 years (Muhs et al. 1992).

Modern Streams

The parks contain portions of three river systems, from north to south, Smith River, Klamath River, and Redwood Creek. These rivers flow through forested and mountainous terrain before discharging into nearshore waters of the Pacific Ocean (see "Coastal Features and Processes"). Active channel and floodplain deposits (see table 3) line the rivers.

The Smith River begins at the confluence of its North Fork and Middle Fork in Smith River National Recreation Area (east of the parks) and flows southwest and then northwest for about 70 km (44 mi) toward the Pacific Ocean, where is discharges near the community of Smith River (about 16 km [10 mi] north of Crescent City). On its route to the ocean, the Smith River has cut deep gorges in the Klamath Mountain rocks (i.e., Josephine ophiolite) but is unconfined in the Franciscan Complex where it developed terraces (**Qt**; see fig. 2).

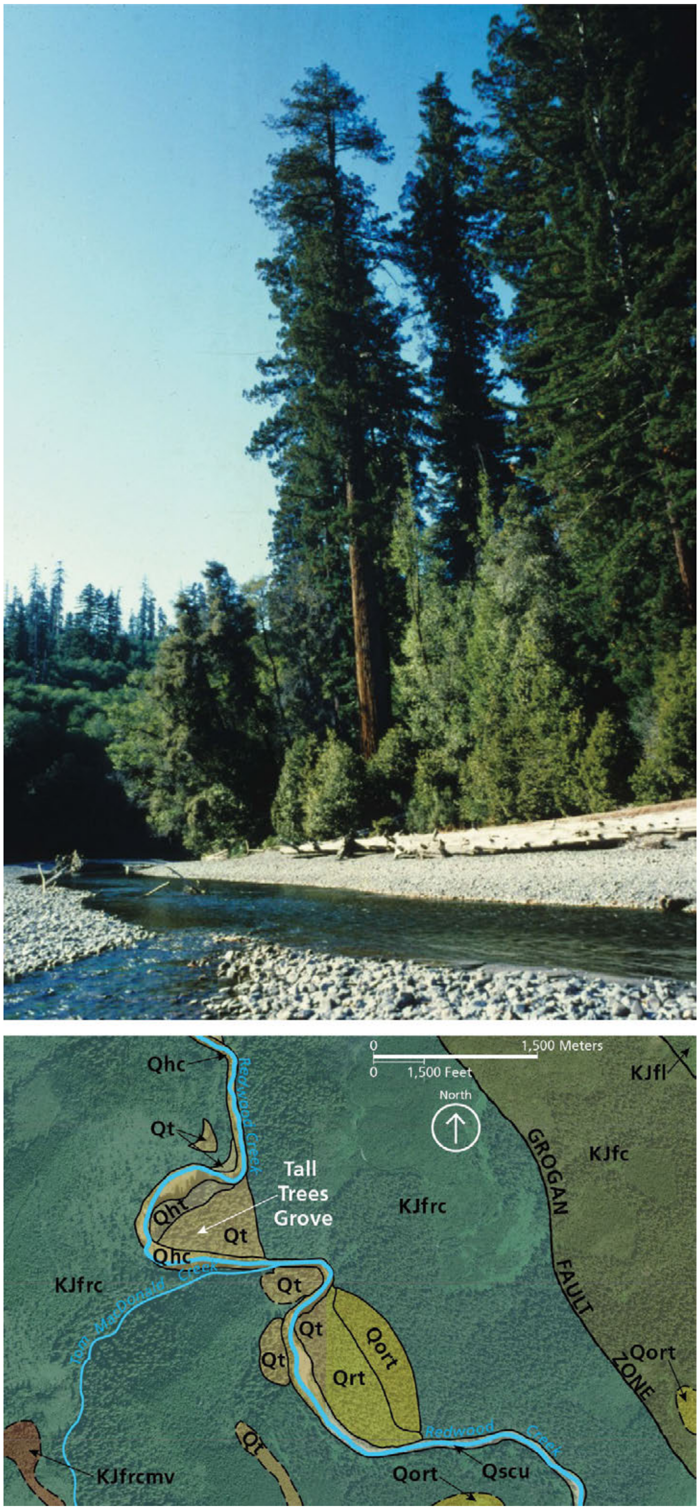

Figure 12. Photograph and geologic map of Tall Trees Grove.
Tall Trees Grove, which is near the confluence of MacDonald and Redwood Creeks, is on a Pleistocene to early Holocene (2.6-million- to approximately 8,200-year-old) stream terrace (Qt). At that location, unit Qht marks the active floodplain and unit Qhc marks the active stream channel. Farther south, along Tall Trees Trail, a series of terraces records a longer history of stream development, from oldest (highest) to youngest (lowest): Qort (less than 2.6 million years old), Qrt/Qt (2.6 million to approximately 8,200 years old), and Qscu (active floodplain and stream channel; less than 11,700 years old). Top: NPS photograph. Bottom: Graphic by Trista Thornberry-Ehrlich (Colorado State University) using GRI GIS data and ESRI ArcGIS World Imagery.

The Klamath River begins in the high desert interior of Oregon, cuts through the Cascade and Klamath Mountains, and discharges into the Pacific Ocean at the mouth of the Klamath River in the parks (see fig. 7 and poster). The first 18 km (11 mi) of the Klamath River are in Oregon; the remaining 460 km (286 mi) are in California. In the vicinity of the parks, the river winds through the Franciscan Complex broken formation (**KJfbf**) and Franciscan Complex mélange unit of Crescent City area (**KJfmc**) before discharging into the ocean (see poster).

Redwood Creek begins southeast of the parks and flows 108 km (67 mi) northwest to the Pacific Ocean, where it discharges at the Redwood Creek estuary (see "Restoration of Redwood Creek Estuary"). Redwood Creek follows the Grogan fault zone, and the shape of the watershed is notably influenced by it (see "Grogan Fault Zone"). The mainstem of the creek drops out of the headwaters to become a low gradient stream with short tributaries draining steep hillsides. A portion of the lower watershed and the spit (**Qds** and **Qbs**) across the estuary are within the parks (see poster). The upper watershed is mostly private timber lands and ranches (North Coast Regional Water Quality Control Board 2021).

The drainage areas of the Smith River and Redwood Creek are relatively small at 1,640 km^2 (632 mi^2) and 720 km^2 (278 mi^2), respectively (Redwood National Park 1985). By contrast, the Klamath River drains an extensive watershed that covers 40,000 km^2 (15,000 mi^2). By average discharge, the Klamath is the second largest river in California after the Sacramento River (National Wild and Scenic Rivers System 2019).

The Klamath and Smith Rivers are designated "wild and scenic" by both the California and national systems (National Park Service 2016a). The California segment of the Klamath River that is designated as wild and scenic begins 1,100 m (3,600 ft) below Iron Gate Dam (one of four dams on the river; see "Dam Removal in the Klamath River Watershed") and ends at the Pacific Ocean. By contrast, the Smith River has no dams and flows freely and naturally for its entire length; it is the only major river system in California that is free of dams (National Wild and Scenic Rivers System 2019). Redwood Creek also is free flowing and has no dams, though a few agricultural diversions occur in the last 5 km (3 mi) upstream from the river's mouth, and flood control levees confine flow through the Redwood Creek estuary (see "Restoration of Redwood Creek Estuary"). Moreover, Redwood Creek is listed as sediment and temperature impaired under section 303(d) of the Clean Water Act (see "Redwood Creek and the Clean Water Act").

Stream Processes and Coast Redwoods

Stream terraces, which are commonly referred to as "alluvial flats," are prime habitat for coast redwoods (fig. 12). Stream processes can affect the health of redwood trees on alluvial flats in many ways. Benefits include the deposition of silt by slow-moving, overbank floodwaters. As flood-deposited silt builds up around the base of a tree, the tree can develop a new root system, referred to as "adventitious roots," which sustains it (Stone and Vasey 1968).

Interestingly, redwood trees serve as the recorders of floods with "silt lines" indicating flood height (fig. 13). Floods with peak flows of around 50,000 cfs (cubic feet per second) occurred in 1953, 1955, 1964, 1972, and 1975 (see fig. 5).

Figure 13. Photograph of flood deposit. The height of a major flood (circa 1970s) is recorded in the bark of a redwood tree that is adjacent to the channel. This deposit records the height of a peak flow of 50,000 cfs. During that flood, silt became embedded into the bark. Although this phenomenon occurs at Tall Trees Grove in the parks, this example is from the Eel River (south of the parks). NPS photograph courtesy of Vicki Ozaki (Redwood National and State Parks).

Detriments of stream processes to redwood trees on alluvial flats include rapid channel aggradation (infilling with sediment). Aggradation can lead to deposition of coarse gravel at the base of a tree, which can physically abrade a tree's trunk or inhibit the formation of adventitious roots, which eventually kills the tree. Channel aggradation also raises the stream elevation during flooding of the main channel and can cause abrasions and damage to riparian redwood trees as they get hit by logs. Moreover, channel aggradation raises the water table, which, if rapid or high enough, can drown the root zone of trees. Another drawback is the creation of a flood channel across an alluvial flat, which can undermine and weaken the root structure of a tree growing on the flat, causing it to fall. Also, streambank erosion can expose roots, eventually undermining a tree and causing it to topple (Madej 2021).

Besides streambank erosion, windfall and landslides can cause a tree to fall into a channel. Depending on channel conditions and the size of the tree, a fallen tree may remain in place or be transported downstream (Madej 2021).

A fallen tree that remains in a stream channel is referred to as "large wood" or "woody debris." In steep streams, large wood dissipates streamflow energy, reducing channel incision. In addition, large wood influences sediment storage in headwater streams. It also has many ecological benefits, including providing shelter to fish from predators, creating habitat diversity for fish and other aquatic organisms, and controlling pool formation. The percentage of pools formed by large wood is highest in small streams, but large wood also is important in influencing pool development in larger streams and rivers (Madej 2021).

Wood loading (the amount of large wood in a stream channel) varies widely, but streams draining old-growth forests have higher loadings than those draining second-growth forests (Madej 2021). Old-growth redwood trees have extremely large biomass, with trunk-wood volumes of 700 to 1,000 m^3 (900 to 1,300 yd^3). They also are very decay resistant (Noss 2000). Consequently, when old-growth trees fall into a river channel, they have a large and persistent influence on in-channel wood loading and channel form. Residence times for individual pieces of in-channel wood can exceed 200 years (Keller and Tally 1979).

Coastal Features and Processes

Using bedrock, the parks' coast can be subdivided into five distinct segments, from north to south (see fig. 7): (1) Battery Formation (**Qby**); (2) Franciscan Complex broken formation (sandstone; **KJfbf**), (3) Franciscan Complex mélange unit of Crescent City (**KJfmc**), (4) Prairie Creek Formation (**QTpc**), and (5) Franciscan Complex Redwood Creek schist (**KJfrc**). Previous sections in this chapter highlighted these bedrock units (see "Franciscan Complex," "Prairie Creek Formation," and "Battery Formation"). Table 4 summarizes the geologic features associated with these segments of the coast.

In addition to bedrock, sediment discharged from creeks and rivers is another important component of the parks' coast. The Klamath River and Redwood Creek discharge freshwater and sediment (silt and coarser materials) into the nearshore zone. Water turbidity in nearshore waters is frequently high during winter months due to suspended silt (fig. 14). Bedload (sand, gravel, cobbles) contributes to offshore systems.

Additionally, nearshore processes (waves and coastal currents) significantly affect coastal areas. Except in the lee of Point Saint George (north of the parks), the coast is fully exposed to waves generated in the North Pacific. Particularly during winter months, algae and animals may be torn from rock surfaces by wave impacts and transported by coastal currents. The California Current (fig. 15), which flows south, dominates sediment transport along the coast.

Shoreline Length

The parks' foundation document (National Park Service 2016a, p.4) and other NPS publications commonly describe the parks as having "37 miles of coastline," but shoreline lengths reported in NPS publications are wrought with inconsistencies (Curdts 2011). Park managers have verified the length of the parks' shoreline using National Oceanic and Atmospheric Administration (NOAA) Continually Updated Shoreline Project (CUSP; see "Additional References, Resources, and Websites"), which was derived using lidar. According to NOAA CUSP data, the parks have 61,106.4 m (61.1 km or 37.9 mi) of coastline along the mainland. Notably, the "mainland," and thereby the shoreline length recorded by NOAA CUSP, excludes offshore rocks and islands, as well as the banks of river, estuaries, lagoons, and inlets (Dave Best, Redwood National and State Parks, GIS and information management, written communication, 25 March 2021).

Because the GRI focuses on geologic features, a shoreline length that incorporates these features (e.g., sea stacks) is provided in this GRI report. Curdts (2011) reported a shoreline length of 77 km (48 mi) for the parks. In addition, Curdts (2011) reported the area covered by coastal (estuarine, intertidal, and ocean) waters as 2,344 ha (5,793 ac). These numbers reflect the USGS National Hydrography Dataset (see "Additional References, Resources, and Websites"), which uses 1:24,000-scale maps. In the case of the parks, these data include the shorelines of sea stacks and smaller offshore rocks but not the landward banks of estuaries and lagoons (Thom Curdts, Colorado State University, email communication, 30 March 2021).

Table 4. Coastal features and slope stability.

Units are listed from north to south as exposed along the parks' coast (see fig. 7). See "Landslides" for descriptions of landslide types.

Bedrock Exposure	Map Unit	Features	Landmarks	Landslide type
Battery Formation	Battery Formation (**Qby**)	• Consists of sand, clay, and gravel • Marine terraces • Coastal plain	Battery Point	• Affected by wave abrasion and uplift rates of as much as 30 cm (10 in) per 1,000 years • Rockslides near Enderts Beach
Franciscan sandstone	Franciscan Complex, broken formation (**KJfbf**)	• Consists of graywacke (hard, dense, dark gray) sandstone • Steep cliffs • Pocket beaches	• Enderts Beach • Crescent Beach Overlook	Rapid, shallow debris slides
Franciscan mélange	Franciscan Complex, mélange unit of Crescent City area (**KJfmc**)	• Consists of large, resistant blocks of bedrock (future sea stacks) in a shaley matrix • Hummocky terrain • Landslide deposits • Offshore sea stacks	• Footsteps Rock (headland) • Wilson Rock (sea stack) • False Klamath Rock (sea stack) • Modern mouth of the Klamath River • Klamath River Overlook • Flint Rock Head (headland; radiolarian chert) • High Bluff Overlook • White Rock (sea stack) • Split Rock (headland)	Earthflows
Prairie Creek Formation	Prairie Creek Formation (**QTpc**)	• Consists of weakly consolidated sand and gravel • Wide, sandy beach • Ancestral mouth of the Klamath River	• Gold Bluffs • Gold Bluffs Beach	• Cliff failure • Rockslides • Debris slides
Franciscan schist	Franciscan units of Harden and others (1982), Redwood Creek schist (**KJfrc**)	• Consists of schist (strongly foliated, metamorphic rock with eminently visible mineral grains, particularly mica, which are arranged parallel, imparting a distinctive sheen or "schistosity") • Marine terraces (**Qmt**) on **KJfrc** • Narrow beach	• Mussel Point • Redwood Creek estuary	Rockslides

Figure 14. Photograph of sediment plume, circa 1980s.
On their way to the Pacific Ocean, the Klamath River and Redwood Creek flow through bedrock and surficial deposits, picking up eroded sediment that they discharge at their mouths. Rivers play a crucial role in replenishing sand lost from beaches. As shown here at the mouth of Redwood Creek, much sediment is discharged during winter storms. NPS photograph courtesy of Vicki Ozaki (Redwood National and State Parks).

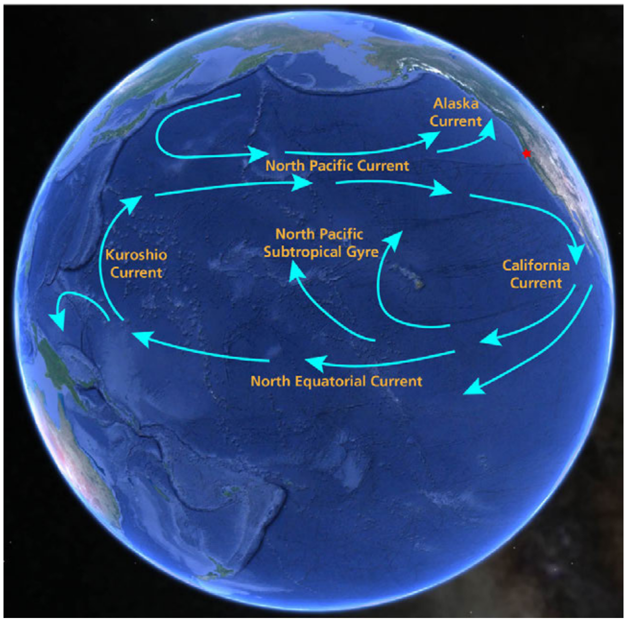

Figure 15. Illustration of general circulation patterns in the Pacific Ocean.
The California Current dominates the flow pattern along the parks' coast (red star). The California Current represents the eastern branch of the North Pacific Subtropical Gyre and refers to the generally equatorward flow along the west coast of the continental United States and Mexico. Source waters for the California Current derive from the North Pacific Current, which separates into the California Current and the Alaska Current (a poleward flowing component) well offshore of North America, just south of 50°N (Reid and Arthur 1975; Wyrtki 1975). Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Borgeld et al. (2007, figure 17).

Coastal Slope Stability

Underlying geology is responsible for slope stability along the coast (Borgeld et al. 2007). A primary area of concern for park management is Last Chance Grade (see "Landslides").

Landslide deposits are mostly associated with the Franciscan Complex mélange unit of Crescent City area (**KJfmc**) and the Franciscan Complex broken formation (**KJfbf**), which are found in the northern portion of the parks (see fig. 7 and poster). Earthflow-type landslides are characteristic of the mélange (**KJfmc**). Earthflows are associated with surficial deposits and weathered bedrock with many internal slide planes; movement resembles the flow of a viscous liquid (Wills 2000). Rockslide-type landslides are characteristic of the broken formation (**KJfbf**). A rockslide moves as an intact block. Rockslide-type landslides are associated with deep-seated bedrock sliding along shear zones (areas of weakness along which displacement takes place) (Wills 2000).

South of Mussel Point, one landslide deposit occurs in the Franciscan Complex, Redwood Creek schist (**KJfc**; see poster). Dell'Osso et al. (2002b) identified this landslide type as a rockslide (see the geohazards GRI GIS data set).

In addition, the cliffs at Gold Bluffs Beach (i.e., Prairie Creek Formation, **QTpc**) are prone to failure. The entire bluff has either very high or high landslide potential (Dell'Osso et al. 2002b). Landslide types along the Gold Bluffs include rockslide and debris slide. Rockslides are composed of bedrock in which much of the original structure is preserved. Debris slides are a loose combination of surficial deposits, rock fragments, and vegetation (see "Landslides").

Sea Stacks

Map units: **KJfmcu** and possibly **KJfbf**

Created by the erosive powers of waves and winds, sea stacks are a notable geologic feature along the parks' coast. They are the remnants of sea cliffs and mark where cliffs once stood. As such, sea stacks are composed of the same rock type as the adjacent sea cliffs. Sea stacks provide rookeries for sea birds and haul-outs for sea lions.

From north to south, the parks have four named sea stacks: Sister Rocks (not mapped, but possibly composed of **KJfbf**), Wilson Rock (**KJfmcu**), False Klamath Rock (**KJfmcu**), and White Rock (**KJfmcu**) (see poster). The parks' coast also has thousands of smaller offshore rocks (Dave Best, Redwood National and State Parks, GIS and information management, written communication, 25 March 2021).

Sea stacks are primarily associated with the Franciscan Complex mélange unit of Crescent City area (**KJfmc**; see table 4 and poster). This mélange unit consists of an erodible shaley matrix (sheared shale and mudstone) with individual blocks of bedrock composed of greenstone (metavolcanic rock with a green color due to its mineral content; **KJfmcgs**), metagraywacke (**KJfmcmg**), and radiolarian chert (**KJfmcch**). The blocks in the mélange are more resistant to erosion than the shaley matrix, so as coastal waves, wind, and weathering wear away the softer material, large blocks of bedrock are left behind to form sea stacks.

Notably, the GRI GIS data show sea stacks as Franciscan Complex mélange unit of Crescent City area, undifferentiated (**KJfmcu**; u = undifferentiated) because the lithology (physical description or classification of rocks and sediment based on characteristics such as color, mineral composition, and grain size) of these bedrock blocks was not confirmed in the field. Sea stacks were mapped from a distance or using aerial photographs (Delattre and Rosinski 2012).

With respect to other map units that are exposed along the coast, the Prairie Creek Formation (**QTpc**), which composes the Gold Bluffs, has no sea stack associated with it because the loosely consolidated sand and gravel of the formation lacks the integrity to develop into a sea stack, even temporarily. Furthermore, the Franciscan Complex, Redwood Creek schist (**KJfrc**), which crops out along the coast in the southern portion of the parks (see fig. 7 and poster), has no sea stack associated with it. Its high clay content and erodibility prohibits sea stack formation. Also, the unit lacks "future sea stack material" (i.e., blocks of bedrock) typical of the mélange.

One sea stack—Sister Rocks—is associated with the Franciscan Complex broken formation (**KJfbf**), which is exposed along the coast north of the Franciscan Complex mélange unit of Crescent City area (see fig. 7 and poster). The source map (i.e., Delattre and Rosinski 2012) and the GRI GIS do not identify the rock unit that makes up Sister Rocks. Assuming, however, that sea stacks are composed of the same rock type as the adjacent sea cliffs, Sister Rocks is probably composed of the broken formation. Another piece of evidence that supports the assumption that Sister Rocks is composed of the broken formation is that resistant greenstone blocks (i.e., "sea stack material") are found in the broken formation, although they are not as abundant as in the mélange. Greenstone blocks are less evident in the broken formation than in the mélange because the fractured sandstone that makes up the bulk of the broken formation is generally more resistant than the goopy mélange matrix. Another possibility is that Sister Rocks is composed of less broken (fractured) sandstone blocks standing out from more closely fractured sandstone of the broken formation that has been eroded away (Marc Delattre, California Geological Survey, senior engineering geologist, email communication, 3 March 2021).

Verification of the lithology of Sister Rocks could be an interesting project for a Scientists in Parks (SIP) participant (see "Guidance for Resource Management"). Obtaining and consulting geologic maps compiled by Delattre and Rosinski (2012), including Ristau (1979), Kilbourne and Maulchin (1981), Aalto and Harper (1982), and Davenport (1984a), would be a preliminary step in such a project. Though unlikely, these maps may have identified the lithology of Sister Rocks even though Delattre and Rosinski (2012) did not. A second step in the project would be to field check the geology of Sister Rocks. Field verification of other sea stacks and other areas mapped as "undifferentiated" (**KJfmcu**) could take place as part of this SIP project.

Significantly, a project focusing on Sister Rocks and other sea stacks would require coordination with other stakeholders. One of the Sister Rocks is an inholding (private land within the parks' boundary) and access to it is across private land. Moreover, access to Sister Rocks or other sea stacks for any kind of study should include prior consultation and coordination with the Yurok Tribe. The Sister Rocks sea stack has tremendous significance to Yurok people as do all of the coastal rocks and sea stacks within their ancestral territory, which extends from Little River in Humboldt County north to Damnation Creek in Del Norte County (Karin Grantham, Redwood National and State Parks, chief of Resource Management and Science, email communication, 24 March 2021).

Beaches and Dunes

Map units: **Qbs** and **Qds**

Beach sand (**Qbs**) at the parks consists of unconsolidated marine-laid deposits of well-sorted, fine- to coarse-grained sand with lesser amounts of silt, clay, shell fragments, and Franciscan cobbles and gravel (Dell'Osso et al. 2002a). Although this material is considered "marine" (i.e., having been transported by coastal currents), beach sand begins as eroded continental material washed to the sea by streams and rivers. This material is stored at the mouths of rivers and in offshore sandbars.

Although the sediment budget along the parks' coast has not been thoroughly studied, the composition of heavy minerals in beach sands at the parks has led investigators to attribute the Klamath River as the primary sediment source (Borgeld et al. 2007). The Klamath River contributes sand to the beaches south of the mouth all the way to Redwood Creek.

North of the mouth of the Klamath River, the parks' coast (between Enderts Beach and the mouth of the Klamath River) is characterized by steep slopes with no beaches. The one exception is the beach at False Klamath Cove, which is directly south of the mouth of Wilson Creek, which is a possible source of sediment to that beach.

Gold Bluffs Beach (south of the mouth of the Klamath River) is the most extensive beach in the parks. In the 1850s, the Gold Bluffs had only a narrow beach between the base of the cliffs and the surf zone. Erosion of the cliff base by wave action resulted in failures of large slabs of the cliffs, depositing old Klamath River fluvial sediments onto the beach and supplying a concentration of fine gold flakes to beach sands. Several commercial ventures were mounted to recover these gold deposits, without notable success (Boyd et al. 1981). Today, the beach is wider than during the 19th century and includes dunes. At a scale of 1:100,000, however, the GRI GIS data (source map, Delattre and Rosinski 2012), do not show any dune deposits (**Qds**) at Gold Bluffs Beach.

The primary location of mapped dune sand (**Qds**) in the parks is at the mouth of Redwood Creek; these dunes extend southward along the seaward side of Freshwater Lagoon (see poster). The most recently formed dunes are the nearest to the beach whereas the older, usually vegetated and stabilized dunes are farthest inland. In California, inland dunes may be as much as 18,000 years old (Caughman and Ginsberg 1987), though dunes at the parks were mapped as Holocene (i.e., less than 11,700 years old).

Estuaries

Map units: **Qha**, **Qhc**, **Qds**, and **Qbs**

An estuary is a partially enclosed body of water where freshwater and saltwater mix. Two estuaries are notable for the parks: one is at the mouth of the Klamath River; the other is at the mouth of Redwood Creek (see fig. 7 and poster). These estuaries, where the Klamath River and Redwood Creek discharge into the Pacific Ocean, are the drowned mouths of rivers. Rising sea level and a subsiding coast flooded these river valleys and created the estuaries.

Broadly defined, the Klamath River estuary is the lower 6.5 km (4.0 mi) of the river subject to tidal fluctuation. Open water, 2–4 m (6–13 ft) deep, and a sand and gravel substrate characterize the lower estuary, which covers an area approximately 2.5 km (1.6 mi) upstream from the mouth. Saltwater can extend as much as 36 km (22 mi) upstream from the coast; tidal-induced changes of surface water elevation have been documented 45 km (28 mi) upriver (Borgeld et al. 2007).

The Redwood Creek estuary is 4.0 km (2.5 mi) west of the town of Orick. Since 1968, flood control levees, constructed by the US Army Corps of Engineers (USACE), have terminated in the Redwood Creek estuary. The levees begin near where Prairie Creek joins Redwood Creek and end 5.3 km (3.3 mi) downstream or about 0.2 km (0.1 mi) inland from the ocean (see "Restoration of Redwood Creek Estuary").

As a result of the formation of a spit (narrow tongue of sand extending from the shore), the mouths of the Klamath River and Redwood Creek can seal off from direct connection with the Pacific Ocean. Closing of the Klamath River occurs infrequently. By contrast, monitoring of the Redwood Creek estuary shows that closure occurs annually, typically in June or July. The current understanding of the dynamics of the closure of Redwood Creek estuary via spit formation is that strong northwest winds push sand onshore, and when flow of Redwood Creek drops below 120 cfs, it usually closes. While the estuary is closing off, the mouth of Redwood Creek can migrate to the south, with the potential to threaten Kuchel Visitor Center (see poster). In the fall, the first large streamflow will break open the spit (Vicki Ozaki, Redwood National and State Parks, geologist, written communication, 19 August 2020).

Lagoons

Map units: **Qds**, **Qbs**, and **Qha**

Lagoons are shallow bodies of water that do not receive significant freshwater inflow and are separated from the open ocean by a barrier (narrow ridge of sand rising slightly above high-tide level). The lagoons within and in the vicinity of the parks are the drowned mouths of stream valleys. The barriers across the mouth are composed of beach sand (**Qbs**) and/or dune sand (**Qds**).

From north to south, the lagoons within and in the vicinity of the parks are Espa, Freshwater, Stone, Dry, and Big (see poster). Espa Lagoon and a portion of Freshwater Lagoon are within the parks; the three other lagoons—Stone, Dry, and Big—are in Humboldt Lagoons State Park, south of the parks.

Beach sand (**Qbs**) lies between the Pacific Ocean and all these lagoons. The sand barrier separating Freshwater Lagoon from the ocean also consists of dune deposits (**Qds**), which are parallel to but farther inland than the beach deposits.

Espa Lagoon is located east of Gold Bluffs Beach in Prairie Creek Redwoods State Park. Espa Lagoon was open to the ocean until sand buildup at the beach sealed it off. A road was built across the mouth of the lagoon and all flow was directed through a culvert. The lagoon evolved into a freshwater pond (Caughman and Ginsberg 1987) that gradually filled in with sediment that eroded from legacy logging roads. Today, the pond is a wetland—mapped as young alluvial deposits, undifferentiated (**Qha**; Delattre and Rosinski 2012)—covered in red alder, willow, and cattails.

Freshwater Lagoon was sealed off from the ocean in the early 1950s by the construction of Highway 101, which runs along the lagoon's barrier beach (Caughman and Ginsberg 1987). At its northern end, Freshwater Lagoon is connected to the ocean by a large culvert, and ocean water discharges onto the beach there. Rarely does the water height in the lagoon reach the culvert, however (Vicki Ozaki, Redwood National and State Parks, geologist, written communication, 18 August 2020). The map by Delattre and Rosinski (2012) shows shallow areas of Freshwater Lagoon as young alluvial deposits, undifferentiated (**Qha**).

Tsunami Deposits

Although not recorded in the GRI GIS data, tsunami deposits are an interesting geologic and cultural feature at the parks. They also are important for understanding a primary hazard (see "Tsunamis"). Paleotsunami (past tsunami) deposits appear as layers of beach sand interspersed in accumulated peaty mud, which is composed of semi-carbonated plant remains (fig. 16). Paleotsunami deposits contain brackish and/or marine diatoms (Garrison-Laney 1998); these microscopic, single-celled algae indicate a marine origin.

Marshes along the western coast of North America preserve a record of both historic and prehistoric tsunami inundation, including events from far-field (i.e., distant or around the Pacific basin) and near-field (Cascadia subduction zone) sources (see "Tsunamis"). Study locations of paleotsunami deposits include Port Alberni, British Columbia (on Vancouver Island); Cannon Beach, Oregon; and Crescent City, California (Peterson et al. 2013). In addition, Lagoon Creek—a freshwater marsh near False Klamath Cove in the parks (see poster)—has a well-preserved paleotsunami record (Peterson et al. 2011).

Figure 16. Photograph of paleotsunami deposit. Past tsunamis are recorded at Lagoon Creek in the parks. Tsunami deposits appear as sand layers in an accumulated organic-rich, peat-bog deposit. Lagoon Creek is a freshwater marsh protected from ocean waves by a beach berm, 6 m (20 ft) high. A tsunami would have to be robust and large enough to overtop this berm to deposit tsunami sand in the marsh. Dr. Gary Carver (Humboldt State University) extracted sediment cores from the Lagoon Creek in ca. 1996. NPS photograph courtesy of Vicki Ozaki (Redwood National and State Parks).

Lagoon Creek spans approximately 1.1 km (0.7 mi) up a narrow, flat-lying valley. The marsh is protected from the ocean by a beach berm, 6 m (20 ft) high. A surge of sand-laden seawater must have been robust and large enough to overtop the berm to deposit a sand sheet in the marsh. A tsunami is the most likely agent. Storm surges are a less likely explanation of sand-sheet deposition due to the height of the beach berm and the inland extent of sand deposition (Abramson et al. 1998).

Dating back more than 3,000 years, six distinct sand sheets represent past tsunami inundation at Lagoon Creek (table 5). As an indication of the extent of inundation, the thickness of the sand layers tapers from about 20 cm (8 in) near the shore to less than 1.0 cm (0.4 in) near the back edge of the marsh (Abramson et al. 1998).

Researchers have used the record at Lagoon Creek to reconstruct inundation distance and runup height for prehistoric events. Three of the six sand sheets extend the length of the marsh inland from the shore, indicating complete inundation of the stream valley (table 5). Maximum recorded run-ups (height of water) are approximately 10 m (30 ft) high (Peterson et al. 2011).

Table 5. Tsunami deposits at Lagoon Creek.

Sources: Garrison-Laney (1998), Abramson (1998), and Vicki Ozaki (Redwood National and State Parks, geologist, written communication, 20 August 2020).

Event age (years ago)	**Inland extent** ***Note*: Lagoon Creek is ~ 1.1 km (0.7 mi) long.**
~315 (1700 CE)	0.87 km (0.54 mi)
~1,100	1.13 km (0.70 mi)
~1,300	1.06 km (0.66 mi)
~1,600	1.13 km (0.70 mi)
~2,500	1.10 km (0.68 mi)
~3,200	>0.63 km (0.39 mi)

Researchers also have used the record at Lagoon Creek to estimate tsunami recurrence intervals. The estimated mean recurrence interval is 450–540 years (Peterson et al. 2013).

The most recent event recorded at Lagoon Creek took place in 1700 CE (Garrison-Laney 1998). Based on correlation with the “orphan tsunami” of Japan, an exact date of 26 January 1700 can now be assigned to this deposit (Atwater et al. 2015). This puzzling tsunami is documented in Japanese history by samurai, merchants, and villagers who wrote of minor flooding and damage. Some noted having felt no earthquake and wondered what had set off the waves. These early 18th–century writers in Japan would have had no way of knowing that the tsunami was spawned during an earthquake on the Cascadia subduction zone off the coast of northwestern North America (Atwater et al. 2015). Timing for the deposit is compatible with Canadian First Nations oral accounts of an earthquake and tsunami that devastated communities on the Pacific coast on a cold winter night prior to European contact (Clague and Turner 2003).

Like the 1700 CE earthquake and tsunami, the other tsunamis recorded at Lagoon Creek are thought to have originated from great earthquakes on the Cascadia subduction zone (Abramson et al. 1998). Other beach and coastal areas in the parks would have been inundated during these same Cascadia earthquakes (see “Quaternary Faults and Earthquakes”).

Descriptions of subduction earthquakes and tsunamis are part of a long oral history and tradition of Cascadia coastal tribes. Oral histories from Wiyot, Yurok, Tolowa Dee-ni’ Nation, and Chetco vividly describe earthquakes and tsunamis causing great damage and death in coastal villages. Several of the stories reported on by Carver and Carver (1996) and Carver (1998) indicate that indigenous people living on the coast recognized shaking as warnings of an impending tsunami, causing some to flee inland. Recognition of shaking and immediately evacuating to higher ground remains a prime example of life-saving behavior (see “Tsunamis”).

Paleotsunami studies reveal the significance of combining oral histories and scientific research. Several of the oral accounts identified specific locations where an earthquake caused submergence and tsunami inundation of the shore. Guided by these oral histories, investigators were able to find evidence of earthquake-related subsidence and tsunami inundation at several sites (Carver and Carver 1996).

Intertidal Zone

Map units: The GRI GIS data do not contain map units specific to the intertidal zone; however, beach sand (**Qbs**) and exposed bedrock such as the Battery Formation (**Qby**) and Franciscan Complex (**KJfbf**, **KJfmc**, and **KJfrc**) are present in the intertidal zone. Intertidal studies commonly map two habitat types: rocky intertidal (stable rocky substrate) and sand beaches (Boyd et al. 1981; Borgeld et al. 2007; Ammann et al. 2017).

The intertidal zone consists of a strip of land that lies between the high-tide and low-tide lines. This zone is regularly covered and uncovered by the advance and retreat of the tides.

Tides along the west coast of North America are mixed, with two high tides (of differing height) and two low tides (of differing height) roughly every day. The period of repetition is closely tied to a lunar day, or 24 hours 50 minutes. The high tides are referred to as higher high water (HHW) and lower high water (LHW). The two low tides are known as higher low water (HLW) and lower low water (LLW). Two standard measures that describe the average highest and lowest daily tides are the mean higher high water (MHHW) and mean lower low water (MLLW), respectively. The mean diurnal tidal range marks the vertical difference between MHHW and MLLW.

The tidal measuring station closest to the parks is operated by the National Ocean Service (NOS), which is part of NOAA. NOS has operated a water level station (#9419750) in Crescent City since 1933. The mean tidal range is 2.09 m (6.87 ft). The maximum and minimum observed tides were 1.16 m (3.79 ft) above MHHW and 1.04 m (3.42 ft) below MLLW, respectively (National Oceanic and Atmospheric Administration 2021).

In general, plants and animals of the intertidal zone (fig. 17) are hardy and adaptable, able to withstand periodic exposure to air and the force of pounding surf. Intertidal communities inhabit sandy beaches, coves, estuaries, wharf pilings, and stable rocky substrate, including rock faces, crevices, the undersides of rocks, and tidepools (pools of water left by an ebbing tide in a rock basin).

Enderts Beach Cove, which is about 6 km (4 mi) south of Crescent City (see poster), provides the most popular access to tidepools in the parks. The cove is frequently visited by educational groups and NPS personnel conducting tours of the intertidal zone. In this small area, Franciscan Complex broken formation (**KJfbf**) extends seaward from the base of the cliffs. This exposure is resistant to erosion and forms rocky benches that provide habitat for many sessile (attached) intertidal organisms (Borgeld et al. 2007).

The mouth of Damnation Creek is another popular destination for viewing intertidal communities. A trail from Highway 101 provides coastal access. Larger rocks host a narrow band of intertidal plants and animals. Species capable of withstanding severe wave shock occur on seaward surfaces (Boyd et al. 1981).

The Multi-Agency Rocky Intertidal Network (MARINe) established long-term monitoring at Enderts Beach Cove and Damnation Creek. Monitoring, which is conducted primarily by researchers from the parks and the University of California Santa Cruz, targets the following species: acorn barnacles (*Chthamalus/Balanus*), California mussel (*Mytilus*), dwarf rockweed (*Pelvetiopsis*), turfweed (*Endocladia*), and ochre star (*Pisaster*). In addition, motile (can move from one place to another) invertebrates, mussel size structure, and water temperature are monitored (see https://marine.ucsc.edu/sitepages/enderts.html and https://marine.ucsc.edu/sitepages/damnation-lt.html; accessed 13 January 2021).

Offshore Geologic Features

Map units: The GRI GIS data do not contain map units for offshore geology.

The geology of offshore California has yet to be completely mapped. The term “offshore geology” can include geologic features such as sea stacks (see “Sea Stacks”) and smaller offshore rocks that rise above sea level. As used here, however, the term primarily applies to the seafloor.

Figure 17. Photograph of intertidal zone.
Tidepooling (looking for sea life in tidepools) is a popular activity in the intertidal zone at the parks. Formed in depressions and crevices of rocky substrate, tidepools are filled with seawater that gets trapped as the tide recedes. These basins, which typically range from a few inches to a few feet deep and a few feet across, are packed with sturdy sea life such as snails, barnacles, mussels, anemones, urchins, sea stars, crustaceans, seaweed, and small fish; colorful sea stars, sea anemones, and barnacles are shown here. The rocks themselves are composed of Franciscan Complex broken formation (KJfbf). NPS photograph by John Chao.

USGS California Seafloor Mapping Program (see "Guidance for Resource Management") is a source of information about California's offshore resources. Data collected as part of this program have revealed the seafloor of the California coast in unprecedented detail. According to the associated online California State Waters Map Series Data Catalog (Golden 2019; see "Guidance for Resource Management"), as of May 2021, seafloor mapping in the vicinity of the parks (e.g., Crescent City, Klamath River, Gold Bluffs, and Trinidad) is a "work in progress" but data will be added to the catalog as they are completed.

At present, what is known about the offshore geology of the parks primarily comes from five studies conducted in the 1970s and 1980s: Welday and Williams (1975), Boyd and DeMartini (1977), Field et al. (1980), Boyd et al. (1981), and Borgeld (1985). In addition, Borgeld et al. (2007) provided an assessment of coastal and marine resources for the parks (see "Offshore Geologic Resource Management").

Two of these previous studies—Welday and Williams (1975) and Boyd et al. (1981)—provided offshore geologic maps. Welday and Williams (1975) compiled a map (scale 1:500,000) that shows the lithology and areal extent of offshore surface sediments along the entire coast of California. The Welday and Williams (1975) map has a bathymetric base and shows some submarine canyons though no geomorphic features (e.g., deltas, submarine fans, or wave-cut platforms) or geologic structures (e.g., faults or fracture zones). Boyd et al. (1981) provided a sketch map (no scale) of the lithology of the offshore surface sediments along the parks' coast. In addition, figures in Field et al. (1980) show a preliminary geology map; a preliminary structural map; a sketch map of areas of seafloor instability; and a sketch map of areas of erosion, transport, and deposition of sediments.

Limitations of previous maps include small scale (less detail than may be useful for resource management), lack of thickness of the mapped units, and no assigned ages of map units. Modern techniques have helped to advance geologic mapping of offshore areas (see "Offshore Geologic Resource Management").

A different type of offshore mapping is benthic habitat mapping. The National Park Service is in the process of compiling benthic habitat maps for the 88 coastal, ocean, and Great Lake parks in the National Park System (see "Offshore Geologic Resource Management"). Redwood National and State Parks is one of these 88 parks. Although benthic habitat maps may include substrate (seabed materials) as well as geomorphic features such as sediment wave deposits (formed by strong tidal currents) or marine sand bars, they are primarily produced using an ecological classification system such as Coastal and Marine Ecological Classification Standard (CMECS; see Federal Geographic Data Committee, Marine and Coastal Spatial Data Subcommittee 2012). Moreover, the focus of benthic habitat mapping differs from geologic mapping; that is, geomorphic features and substrate are viewed as the physical environment in which benthic biota occur. As such, benthic habitat maps are not, strictly speaking, geologic maps.

At present, two studies—Boyd and DeMartini (1977) and Boyd et al. (1981)—documented "benthic habitats" at the parks, though the terminology "benthic habitat mapping" had not yet come into use at the time of these studies. The study area for both investigations was 55 km (34 mi) of coast in southern Del Norte County and northern Humboldt County, that is, the "Redwood National Park Area of Special Biological Significance." Although both these studies provided qualitative descriptions and observations about intertidal and subtidal habitat types, only Boyd et al. (1981) provided a map (mentioned previously). Mapping by Boyd et al. (1981) delineated two intertidal habitats: (1) rocky shores (now usually referred to as "rocky intertidal") and (2) sand beaches (see "Intertidal Zone"). In addition, mapping by Boyd et al. (1981) delineated four subtidal habitats: (1) "rocky habitat not influenced by sand" was observed on both nearshore and offshore rocks; (2) "rocky habitat influenced by sand" was observed in water about 6 m (20 ft) deep and consisted of bedrock surrounded by sand; (3) "rocky habitat influenced by sediments finer than sand" was only observed about 0.4 km (0.2 mi) north of the mouth of the Klamath River; and (4) "sandy habitat" was observed throughout the survey area and ranged in extent from small deposits between boulders and bedrock to large subtidal expanses. Divers observed and mapped these subtidal habitats during a scuba survey between the mouth of the Klamath River and the parks' northern boundary, thus mapping of subtidal habitats did not cover the entire study area.

Based on previous studies, a general description of the parks' offshore area is provided here. Broadly, the parks' offshore geologic features are part of the continental margin (drowned edge of the continent), which in California extends from the coast to about 135 m (440 ft) water depth and varies in width from 15 to 30 km (9 to 19 mi) across (Borgeld 1985). With respect to plate tectonics, the continental margin off northern California has a young and complex morphology developed in response to late Tertiary and Quaternary plate motion (Field et al. 1980). The Cascadia subduction zone and Mendocino fracture zone dominate the offshore picture (see fig. 21).

Notably, geologic features discussed elsewhere in this GRI report do not end at the shore. Although hidden from view by the waters of the Pacific Ocean, rock formations extend seaward. Moreover, faults and folds continue their north–northwest trend offshore. Active faults displace the seafloor and influence the locations of sediment depocenters. Folding has created as much as 200 m (660 ft) of seafloor relief (Field et al. 1980).

Other distinctive features of relief on the seafloor include areas of uplift such as ridges and knolls and areas of incision such as submarine canyons. Eel Canyon, offshore from Crescent City, is steep, narrow, and meandering whereas Trinity Canyon, offshore from Big Lagoon, is broad and bowl-shaped.

In some areas of the seafloor, well-developed thalwegs (line connecting the lowest/deepest points along a stream bed) and natural levees are indicative of active channels. In other areas, the seafloor is characterized by a continuous series of migrating channels.

Slumps, slides, and unstable sediment masses cover large areas of the seafloor; the size of slumps, for instance, varies from 10s to 1,000s of meters on a side. Transport of sediment takes place via sediment-laden turbidity flows (Field et al. 1980). Active or recent rotational slumps and debris slides, which are characterized by hummocky seafloor, are evidence of separation and movement. Unstable surface sediments show bulging, separation, and other effects indicative of failure. Chaotic subsurface sediments (recorded in seismic reflection data) are interpreted as buried slumps and slides (Field et al. 1980).

The continental margin of California is an active depositional regime (Field et al. 1980). Offshore deposits consist of a variety of clastic (fragments of rock) sediments of various sizes, including gravel, sand, fine sand, and sandy mud. In addition, some offshore deposits include shells or shell fragments, as well as shell sand. Offshore deposits also may include peat (Welday and Williams 1975; Boyd et al. 1981). Other components of offshore sediments include diatoms, sponge spicules, foraminifera, calcareous nannofossils (fossil of a minute planktonic organism), radiolarians, fish remains, volcanic glass, and glauconite (greenish silicate [silicon + oxygen] mineral indicative of very slow sedimentation) (Field et al. 1980).

In general, fine to very fine sands cover the nearshore zone (to a water depth of 50 to 60 m [164 to 197 ft]) of the continental margin; silts and clays dominate the middle shelf (water depths from 60 to 120 m [197 to 394 ft]); and variable sediments, ranging from sandy silts to silty sands, cover the outer shelf (deeper than 120 m [394 ft]) (Borgeld 1985). Although the seafloor is actively receiving sediments, many areas are devoid of them. Canyons are a notable example. Apparently, sediments do not accumulate in canyons because of steepness or water/sediment through-flow (Field et al. 1980).

Rivers are the dominant source of sediment to offshore areas. Aerial photographs (see fig. 14) and satellite imagery show large plumes of suspended sediment; these plumes can extend across the entire continental margin. The provenance of these fluvial sediments lies in the granitic and metamorphic rocks of the adjacent Klamath Mountains and the Franciscan rocks of the northern California Coast Ranges (Field et al. 1980). The contribution of coastal erosion and bluff retreat to offshore sedimentation at the parks is unknown.

Geologic Resource Management Issues

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

During the 2004 scoping meeting (see scoping summary by Covington 2004) and 2019 conference call, participants (see "Acknowledgements") identified the following resource management issues. The issues are ordered alphabetically, not by management priority.

- Climate Change, including carbon sequestration, resilience of redwoods, slope stability, and sea level change
- Coastal Resources Management
- Dam Removal in the Klamath River Watershed
- Landslides, including a discussion of Last Chance Grade
- Marijuana Cultivation Sites
- Offshore Geologic Resource Management
- Quaternary Faults and Earthquakes
- Redwood Creek and the Clean Water Act
- Redwood Creek Streamflow
- Restoration of Redwood Creek Watershed
- Restoration of Redwood Creek Estuary
- Tsunamis

Climate Change

Although climate change planning is beyond the scope of the GRI, a discussion of climate change is included in this report because of the potential disruption that it may cause to the parks' resources, including geologic resources. Park managers are directed to the NPS Climate Change Response Program to address climate change planning (see "Guidance for Resources Management").

The parks' foundation document (National Park Service 2016a) identified climate change planning—including a vulnerability assessment, scenario plan, and adaptation strategy—as a medium priority management need. Improved climate models for parklands are another planning need.

Some basic information about climate change is available for the parks. The following investigations were specifically conducted by or for the National Park Service:

- Davey et al. (2007) completed a weather and climate inventory for the Klamath Network, including the parks.
- Monahan and Fisichelli (2014)—which updated the inventory by Davey et al. (2007) and provided park-specific information—reported that none of the 14 temperature or precipitation variables studied were "extreme" for the parks. The study defined "extreme" (e.g., extreme warm, extreme wet) as exceeding 95% of the historical range of conditions. The study noted, however, that although recent (1901–2012) values are not "extreme," future changes in climate are likely to manifest themselves as more intense storms, floods, or drought.
- Melnick et al. (2016) studied how climate change has the potential to affect cultural landscapes within the Pacific West Region of the National Park System; the Lyons Ranches Historic District, located in the Bald Hills of the parks, was one of six case studies highlighted in the report. Melnick et al. (2016) provided maps of both wildfire hazard potential and landside incidence in the historic district, which may be of use for climate change planning in that area of the parks.

Other studies in the region, though not particular to the parks, noted that climate change will likely alter runoff patterns by causing a precipitation shift from snow to rain (Kiparsky and Gleick 2003), earlier snowmelt (Knowles et al. 2006), lower summer flows (Barr et al. 2010), and more intense storms that will increase peak flows (Bates et al. 2008; Doppelt et al. 2008).

Climate change effects on stream temperature within the Southern Oregon/Northern California Coast evolutionarily significant unit (SONCC ESU)—that is, coastal streams between Cape Blanco, Oregon, and Punta Gorda, California (south of the parks)—are already apparent (Isaak et al. 2012). For example, a 0.5°C (0.9°F) per decade increase in water temperature since the early 1960s has taken place in the Klamath River (Bartholow 2005), and model simulations predict a further increase of 1°C–2°C (2°F–4°F) over the next 50 years (Perry et al. 2011). Elevated water temperature stemming from human activities (see "Redwood Creek and the Clean Water Act") is among the most widespread and greatest stressor facing coho salmon (*Oncorhynchus kisutch*) throughout the SONCC ESU

(National Marine Fisheries Service 2014). Coho salmon are particularly vulnerable to climate change due to their need for year-round cool water temperatures (Welsh et al. 2001).

Carbon Sequestration

Carbon sequestration (the process of moderating global climate change by removing carbon dioxide [CO_2] from the atmosphere and storing it in long-term mineral, organic, and oceanic reservoirs) is an important ecosystem service provided by protected natural areas such as the National Park System (Banasiak et al. 2015). This capability of the parks' forests, particularly its old-growth forests, is important enough to warrant mention in one of the parks' six significance statements:

Nearly half of the world's remaining old-growth coast redwood forest, including some of the oldest and tallest trees in the world, are found in Redwood National and State Parks. These forests provide an important refuge for a diverse community of plants and animals and help protect the world's climate through their ability to sequester massive quantities of carbon (National Park Service 2016a, p. 6).

One type of carbon sequestration is vegetative carbon sequestration, which is the sequestration provided through plant growth. Each year, vegetation on NPS lands in the continental United States sequesters 17.5 million metric tons (19.3 million tons) of CO_2. That amount is equivalent to saving the emissions from the combustion of 9 billion liters (2 billion gallons) of gasoline from being released into the air annually. Nearly one-fifth (18.6%) of that total takes place in Everglades National Park (1.8 million metric tons or 2.0 million tons) and adjacent Big Cypress National Preserve (1.4 million metric tons or 1.6 million tons). Vegetation at Redwood National Park sequesters approximately 0.5% of the total or a base minimum amount of 87,394 metric tons (96,335 tons) per year (Banasiak et al. 2015). The total amount of carbon held in vegetation at the parks is 17 million metric tons (19 million tons; Van Mantgem et al. 2013).

Another type of carbon sequestration is soil carbon sequestration. The soils at the parks store an estimated 12 million metric tons (13 million tons) of carbon (Van Mantgem et al. 2013).

Carbon sequestration is a geologic resource management issue for at least two reasons. First, landslides, which are frequent in the parks (see "Landslides"), represent a carbon "cost" (reduction in stored carbon) because they strip carbon-rich soil and vegetation off hillslopes and deliver that carbon to streams (Madej 2009). Second, restoration activities at the parks—including removal of logging roads and management of second-growth forests (see "Restoration of Redwood Creek Watershed")—initially involve a carbon "cost" because these restoration activities reduce stored carbon through emissions of heavy equipment and vehicle fuel, short-term soil loss, and clearing of vegetation (Madej 2021). However, a return to more natural forest systems may provide for enhanced ecosystem carbon storage over the long term (Van Mantgem et al. 2013).

Road removal represents a carbon savings as soil erosion decreases, road surfaces revegetate, and soil organic carbon accumulates (Madej 2021). The total carbon cost for treating 410 km (255 mi) of road (the total treated as of 2009) was 23,000 metric tons (25,000 tons) of carbon whereas the total savings from that work was 68,000 metric tons (75,000 tons) of carbon (Madej et al. 2013). Carbon sequestration will continue to increase as trees grow and soil carbon accumulates (Van Mantgem et al. 2013).

Resilience of Redwoods

Redwood trees play an outsized role in global climate mitigation despite their limited geographic distribution. All the data compiled by the Redwood and Climate Change Initiative—a research program led by Save the Redwoods League and Humboldt State University (see "Guidance for Resource Management")—confirm the vital importance of protecting and restoring these forests throughout their natural range, not least because of their incredible carbon storage capacity and proven viability as a long-term carbon sink. Measurements in Humboldt Redwoods State Park (south of the parks) show that coast redwood trees attain the highest carbon density in the world (Busing and Fujimori 2005).

Stores of individual redwood trees and entire redwood forests provide a relief to the dire outlook caused by climate change (Burns and Sillett 2019). Mature trees alive today have experienced centuries of climatic fluctuations, including extreme weather events, which are predicted to become more frequent (Gonzalez 2017). In addition to their tremendous capacity to sequester carbon, coast redwoods can resist fire, drought, and disease as they grow tall and gain substantial biomass (Burns and Sillett 2019). Findings by Burns and Sillett (2019) show no evidence of redwoods retreating from native forests as the climate changes during the 21st century. These iconic trees are growing at faster-than-expected rates, thereby enhancing arboreal habitats for other species (Sillett and Van Pelt 2007).

Slope Stability

The findings of climate change studies, such as Monahan and Fisichelli (2014), are significant for making predictions about the response of geologic features and processes, such as slope movements, to climate change. Changes in precipitation patterns will influence the type and timing of slope movements in the parks.

In the Redwood Creek watershed, progressive creep (slow downward movement of sediment), ranging from 1.0 to 2.5 mm (0.04 to 0.1 in) per year, dominates on slopes west of the Grogan fault zone. Progressive creep on these slopes responds to annual precipitation (Swanston et al. 1983). Thus, if annual increments of precipitation increase on account of climate change, progressive creep on the slopes west of the Grogan fault zone could increase. These slopes are underlain by sheared and foliated schist (Franciscan Complex, Redwood Creek schist, **KJfrc**).

In the Redwood Creek watershed, complex earthflows (composed of a mixture of fine-grained soil and deeply weathered, disrupted bedrock; see "Landslides") occur predominantly on slopes east of the Grogan fault zone. Movement rates range from 3.0 to 131.0 mm (0.1 to 5.2 in) per year on these slopes and characteristically display dominant rainy-season movement (Swanston et al. 1983). Thus, if precipitation during the rainy season increases in response to climate change, earthflows on the slopes east of the Grogan fault zone could increase. These slopes are underlain by sheared graywacke and mudstone (Franciscan Complex coherent unit of Lacks Creek, **KJfl**, and Franciscan Complex incoherent unit of Coyote Creek, **KJfc**).

Swanston et al. (1983) studied the slopes to the east and west of the Grogan fault zone but did not discuss the rocks within the Grogan fault zone. Transitional rocks of the Grogan fault zone (**KJfg**) appear to be extremely susceptible to slope movements (Falls et al. 2003), but the influence of climate change and response to precipitation is unknown.

Any widespread loss of vegetation can affect slope stability (Mary Ann Madej, US Geological Survey, emeritus geologist, written communication, 6 August 2020; see "Restoration of Redwood Creek Watershed"). Thus, the influence of climate change on wildfires and sudden oak death, which cause vegetation loss, is of management concern. Furthermore, changes in vegetation type and distribution may change landslide processes and distribution (Vicki Ozaki, Redwood National and State Parks, geologist, written communication, 19 August 2020).

In addition, wildfires, which may increase in response to drought brought on by climate change, are a concern because of the accelerated erosion and sedimentation that follow them. Of potential interest and use for resource management at the parks are the GRI reports for Bandelier National Monument (KellerLynn 2015) and Tonto National Monument (KellerLynn 2020), which provide detailed discussions of the interplay between wildfire and landslides. The NPS Geologic Resources Division can provide technical assistance (see "Guidance for Resource Management").

Sea Level Change

According to *Sea Level Rise and Storm Surge Projections for the National Park Service* (Caffrey et al. 2018), the parks will experience a rise in sea level of 0.1 m (10 cm or 4 in) by 2030 under all emissions scenarios. By 2050, a 0.2 m (20 cm or 8 in) rise in sea level will take place under all emissions scenarios. By 2100, the parks will experience a rise in sea level of 0.4 m (40 cm or 16 in) under the lowest emissions scenario, or as much as 0.6 m (60 cm or 24 in) under the highest emissions scenario.

Sea level rise is projected to affect estuaries, coastal freshwater marshes, and other low-lying lands; change the amount and location of critical estuarine and brackish habitats for salmon; and increase the salinity of rivers, bays, and groundwater tables (Intergovernmental Panel on Climate Change 2007). Future sea level rise will, thereby, affect the restoration of the Redwood Creek estuary and should be addressed in restoration planning (Vicki Ozaki, Redwood National and State Parks, geologist, written communication, 19 August 2020; see "Restoration of Redwood Creek Estuary").

In a study using a 1-meter rise in sea level, Peek et al. (2015) estimated that the Thomas Kuchel Visitor Center was the parks' most vulnerable asset. Paved Route 900 and the parking lot associated with the Thomas Kuchel Visitor Center are other assets threatened by 1-meter of sea level rise, as are the restroom and day-use picnic area at Lagoon Creek. Park managers are in the planning process with Save the Redwoods League to relocate the Thomas Kuchel Visitor Center to the mouth of Prairie Creek (see poster).

Other impacts of climate change to coastal resources are discussed in "Coastal Resources Management."

Coastal Resources Management

According to *Assessment of Coastal and Marine Resources and Watershed Conditions at Redwood National and State Parks, California* (Borgeld et al. 2007), the overall health of the parks' coast is good but influenced by surrounding land uses and human activities. Careful monitoring, ongoing assessment, and discussion and collaboration with other stakeholders in the region are all critical to maintaining the pristine condition of the coast.

Borgeld et al. (2007) described geologic, hydrologic, and biologic resources of coastal water bodies within the parks, summarized potential threats to these resources, and made recommendations for managing these resources. That assessment noted considerable existing information on the flora, fauna, and function of the parks' watersheds, which empty into the Pacific Ocean. Much less, however, is known about the impact of these watersheds on the parks' coastal waters.

At present, monitoring activities along the parks' coast consist of monitoring intertidal communities by the Klamath Inventory & Monitoring Network. This work is conducted through a partnership with MARINe (Multi-Agency Rocky Intertidal Network), which is a regional intertidal monitoring network sponsored by the Minerals Management Service (MMS; https://www.nps.gov/im/klmn/intertidal.htm; see Ammann and Raimondi 2008; Ammann et al. 2017).

With respect to geologic resources, Borgeld et al. (2007) made the following recommendations:

- Conduct basic mapping of the coastal and nearshore environment to classify habitats and investigate the possible existence of submerged cultural resources within the parks' boundaries (see "Offshore Geologic Resource Management"). The assessment recommended that park managers develop a collaborative partnership with the California Center for Integrative Coastal Observation, Research and Education (CICORE). CICORE is a coastal ocean monitoring program supported by NOAA and conducted by several marine-related institutions of the California State University system. As a part of the CICORE program, key remote sensing measurements are being made along the California coast using both hyperspectral overflights and marine acoustic swath mapping to characterize coastal habitats, among other tasks. Future overflights or acoustic mapping may be able to include the parks.
- Characterize the coastal and nearshore currents along the parks' coast. The assessment recommended that park managers develop a collaborative partnership with the Coastal Ocean Current Monitoring Program (COCMP). This program, which is supported by the California Coastal Conservancy, is designed to provide measurements and model predictions of coastal ocean currents. At present, a single surface current radar (SCR) system is sited on the coast in Crescent City and is operated by Oregon State University. As the regional representative of COCMP, Humboldt State University intends to establish as many as four more SCR systems along the north coast of California to measure and generate hourly maps of ocean surface currents. The proposed systems would provide roughly 5 km (3 mi) resolution. Higher resolution observations in the parks will likely be needed, either on a temporary or permanent basis, to support detailed understanding, monitoring, and prediction of flows closer to the shore. Such measurements would also likely support the development of improved predictive models. A collaborative partnership with COCMP would improve the prospects for justification of such a high-resolution system for monitoring currents at the parks.
- Identify littoral (coastal current) cells and develop a beach sediment budget for the parks' coast. Researchers have suggested that much of the parks' coast is accreting, which contrasts the coast elsewhere in Oregon and California. Researchers also have suggested that the parks' beaches may be sediment impaired. This apparent contradiction clearly indicates the need for a closer examination of the sources and sinks of sediment along the parks' coast. Borgeld et al. (2007) suggested that the development of a sediment budget would be the most direct method to work toward a better understanding of local coastal processes and responses. Mirroring this recommendation, the parks' foundation document (National Park Service 2016a) identified sediment transport and hydrodynamic modeling (sediment risk data and analyses) as a medium-priority planning and data need.
- Characterize the erosional and depositional environments along the parks' coast, including the rates of erosion and deposition. As part of a national assessment of shoreline change, Hapke et al. (2006) investigated historical shoreline change and associated land loss along the sandy shorelines of California's coast. Shoreline-change data are scheduled to be collected every three years using lidar mapping techniques on USGS overflights, but data are not analyzed for the parks at the present time. Perhaps a cooperative agreement could be developed to broaden the current area of analysis to include the parks' coast. Mirroring this recommendation by Borgeld et al. (2007), the parks' foundation document (National Park Service 2016a) identified coastal and barrier beach modeling as a medium-priority planning and data need.

Beaches and dunes are other coastal resources at the parks. At present, natural dune processes are being disrupted by European beach grass (*Ammophila arenaria*). This invasive, nonnative plant stabilizes dunes, disrupting natural sand transport, which in turn changes the dune ecosystem and threatens native species (Vicki Ozaki, Redwood National and State Parks, geologist, written communication, 19 August 2020).

The parks' foundation document (National Park Service 2016a) identified a beach and dune management plan as a high priority need. As stated in the foundation document, the plan will address human use and access (including traditional tribal uses and vehicular use by staff) to the beaches and dunes, wildlife concerns, invasive plant management, opportunities for education and interpretation, and regulations and enforcement. Significantly, this list does not include geomorphic processes. If coastal geomorphic expertise is needed, park managers can request technical assistance regarding the parks' beaches and dunes from either the NPS Geologic Resources Division or the NPS Water Resources Division (see "Guidance for Resource Management").

Dam Removal in the Klamath River Watershed

Between 1911 and 1962, the California Oregon Power Company ("Copco") built four hydroelectric dams—John C. Boyle, Copco Number 1, Copco Number 2, and Iron Gate—on the Klamath River. The John C. Boyle Dam is in Oregon; the other three dams are in California. The most downstream reservoir (Iron Gate) is 306 km (190 mi) upstream from the Pacific Ocean. That dam poses the first barrier to spawning salmon on the river (National Wild and Scenic Rivers System 2019).

These four dams and associated reservoirs are currently owned and operated by the energy company now known as PacifiCorp (formerly Copco). To improve spawning and survival of fish species protected under the Endangered Species Act, efforts to remove these dams were formalized in the 2010 signing of the Klamath Hydroelectric Settlement Agreement (KHSA). Signatories of the 2016 amended KHSA—including the States of California and Oregon, local governments, tribal nations, PacifiCorp, irrigators, and several conservation and fishing groups—appointed an independent nonprofit organization, Klamath River Renewal Corporation (KRRC), to take ownership of the four dams and then remove them, restore formerly inundated lands, and implement required mitigation measures in compliance with all applicable federal, state, and local regulations. KRRC's work is funded by PacifiCorp customer surcharges and California Proposition 1 water bond funds. KRRC anticipates that drawdown and dam removal will take place in 2022 (Klamath River Renewal Corporation 2019). *Definite Plan for the Lower Klamath Project* (Klamath River Renewal Corporation 2018), which was filed with the Federal Regulatory Energy Commission in 2018, provides details of the dam removal process.

The "big question" for the parks is what changes will take place in the lower Klamath River basin and along the coast following dam removal (GRI conference call, 18 November 2019). A discussion of watershed response to dam removal is beyond the scope of the GRI, but the US Bureau of Reclamation anticipates that the majority of the reservoirs' deposits will mobilize during reservoir drawdown and during winter storms, and the river will quickly regain its former channel (US Bureau of Reclamation 2011; see also Major et al. 2012; East et al. 2015; Foley et al. 2017; Lohan 2019). In addition, park managers are referred to restoration efforts in Olympic National Park following the removal of the Elwha Dam, which is among the best-studied dam removal projects in the world (Duda et al. 2019; see National Park Service 2020). Studies in Olympic National Park included geomorphic response of the Elwha River channel to a massive sediment pulse released during dam removal (East et al. 2018), ecological responses to dam removal (Bellmore et al. 2019), and lessons learned during the removal project (Duda et al. 2019). Findings from these studies may help the parks' managers plan for changes in the Klamath River basin.

Landslides

Irregular, knobby outcrops of the landslide-prone rocks of the Franciscan Complex (fig. 18) dominate much of the parks' topography (Fuller et al. 2015). The Franciscan Complex has been sheared and broken by tectonic activity, making it relatively weak, easily weathered, and naturally susceptible to landsliding (downward movement of a landslide) as well as erosion. Heavy rainfall, high regional uplift rates, and ongoing seismic activity combined with erodible bedrock and soils produce widespread features of landsliding; these factors also produce relatively high sediment input to streams (Falls et al. 2003).

Figure 18. Photograph of Franciscan Complex and resulting landscape.
The landslide-prone Franciscan Complex makes up much of the parks' landscape. South of the mouth of the Klamath River (near Flint Rock Head), the mélange unit of Crescent City area (KJfmc) yields hummocky terrain indicative of landslides. The red arrows point to a scarp at the top of a landslide deposit. Photograph (Image 7393, taken 13 October 2002) by California Coastal Records Project. Copyright © 2002–2021 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.californiacoastline.org, used by permission.

The following three GRI products graphically display landslide information:

- The geology GRI GIS data set compiled mapping by Delattre and Rosinski (2012) and Dell'Osso et al. (2002a). Mapping by Delattre and Rosinski (2012) shows landslide deposits (**Qls**) in the Crescent City and Orick quadrangles (see fig. 1), that is, areas in the parks excluding the Redwood Creek watershed. Along the coast in the northern portion of the parks, Delattre and Rosinski (2012) mapped landslide deposits associated with the Franciscan Complex mélange unit of Crescent City area (**KJfmc**) and the Franciscan Complex broken Formation (**KJfbf**). These deposits encompass areas affecting Last Chance Grade (see "Last Chance Grade"). In the southern portion of the parks, landslide deposits are associated with the Franciscan Complex Redwood Creek schist (**KJfrc**; see poster). Notably, landslide mapping by Delattre and Rosinski (2012) was limited to relatively large, deep-seated landslides and slide complexes where the authors considered the existence of landslides as definite or probable. That mapping project was not intended to represent an inventory of all recognized or suspected landslides in the area.
- The poster displays the geology GRI GIS data set and, therefore, includes landslides mapped by Delattre and Rosinski (2012) in the Crescent City and Orick quadrangles (see fig. 1). Notably, no landslide deposits appear in the Redwood Creek watershed in the geology GRI GIS data set or on the poster. This is misleading because the watershed has ample landslides, including earthflows, debris slides, rockslides, and debris flows (discussed below); the map by Delattre and Rosinski (2012) simply does not provide coverage of the Redwood Creek watershed.

- The geohazard GRI GIS data set, which compiled the map by Dell'Osso et al. (2002b), shows landslide deposits (discussed below) and landslide potential in the Redwood Creek watershed. Dell'Osso et al. (2002b) used geologic, landslide, and geomorphic data, as well as hillside gradients, to derive this map. Notably, this map shows the most likely future sources of sediment from mass wasting (downslope transport of a mass of rock and/or unconsolidated material under the direct influence of gravity) in the Redwood Creek watershed, which is applicable to restoration efforts (see "Restoration of Redwood Creek Watershed"). Moreover, the data show that more than half of the Redwood Creek watershed has high to very high landslide potential. Weak bedrock materials and steep to very steep slopes are the main contributors to the classifications of highest landslide potential. Active landslides are concentrated in the geologic units on the east side of the Grogan fault. Also, rocks within the Grogan fault zone (**KJfg**) are extremely susceptible to mass wasting (Falls et al. 2003).

Four types of landslide deposits are found in the Redwood Creek watershed, listed from most to least prevalent:

- Debris slides (composed of coarse-grained soil, commonly consisting of a loose combination of all surficial deposits, rock fragments, and vegetation) account for 85.3% of the deposits mapped by Dell'Osso et al. (2002b) in Redwood Creek watershed.
- Debris flows (also referred to as "debris torrents," see Madej 2021; a mass of coarse-grained soil flowing downslope as a slurry) account for 13.4% of the deposits mapped in Redwood Creek watershed.
- Earthflows (composed of a mixture of fine-grained soil and deeply weathered, disrupted bedrock) account for 0.9% of the deposits mapped in Redwood Creek watershed.
- Rockslides (composed of bedrock in which much of the original structure is preserved) account for 0.4% of the deposits mapped in Redwood Creek watershed.

The brief descriptions in the parenthetical notations in the bulleted list (above) are from Wills (2000). Falls et al. (2003), which is the report that accompanies Dell'Osso et al. (2002b), provides full descriptions. Landslide classification (fig.19) and terminology of Dell'Osso et al. (2002b) follows California Geological Survey (2013), which is consistent with definitions presented in Varnes (1978) and Cruden and Varnes (1996).

Other investigations in the Redwood Creek watershed discuss a couple other types of landslides: Madej (2021) discussed forested block slides (see Sonnevil et al. 1987; Swanston et al. 1995) and soil creep. Falls et al. (2003) noted that areas of disrupted ground, which were not conclusively shown to be mass-wasting related, may be caused by shallow soil creep or differential erosion of the underlying bedrock, rather than discrete landslides or earthflows.

A master's thesis by Hare (2003) is an additional resource about landsliding in the Redwood Creek watershed (Mary Ann Madej, US Geological Survey, emeritus geologist, email communication, 6 August 2020). Hare (2003) tested the application and evaluation of SHALSTAB—a GIS-based, physical process–driven model—in the Redwood Creek watershed. Model output was field tested in the Lake Prairie Creek sub-watershed of upper Redwood Creek. Model results proved instructive to the parks' geologists involved in the timber harvest review process at that time.

Last Chance Grade

Last Chance Grade is a segment of Highway 101 that begins about 14 km (9 mi) south of Crescent City and ends where the road intersects Wilson Creek (fig. 20); it is about 5 km (3 mi) long. This landslide-prone segment of the highway is not within the parks, but it is of great concern for park managers because failure of the slope and road would isolate park headquarters, the Maintenance Division, and north park interpreters from the rest of the parks and cripple many divisions' abilities to do work (Vicki Ozaki, Redwood National and State Parks, geologist, written communication, 19 August 2020). A large-scale failure on Last Chance Grade would be felt throughout the region because Highway 101 is the economic lifeline of the north coast. Residents, travelers, and local and regional businesses would be disrupted (California Department of Transportation 2019).

Although Last Chance Grade is not within the parks, possible realignment alternatives to the existing highway are on park lands, and most of the alternatives would impact old-growth forests (California Department of Transportation 2016, 2019). Notably, all the alternative routes go through areas of historic landslides because landslides are common in the area and are difficult to avoid. Whether a new road in these landslide areas will reawaken the slides or even create another situation like Last Chance Grade is unknown. The purpose of early geotechnical investigations, as part of the Last Chance Grade Project, is to collect information that will allow engineers and geologists to refine or validate the locations of the project alternatives.

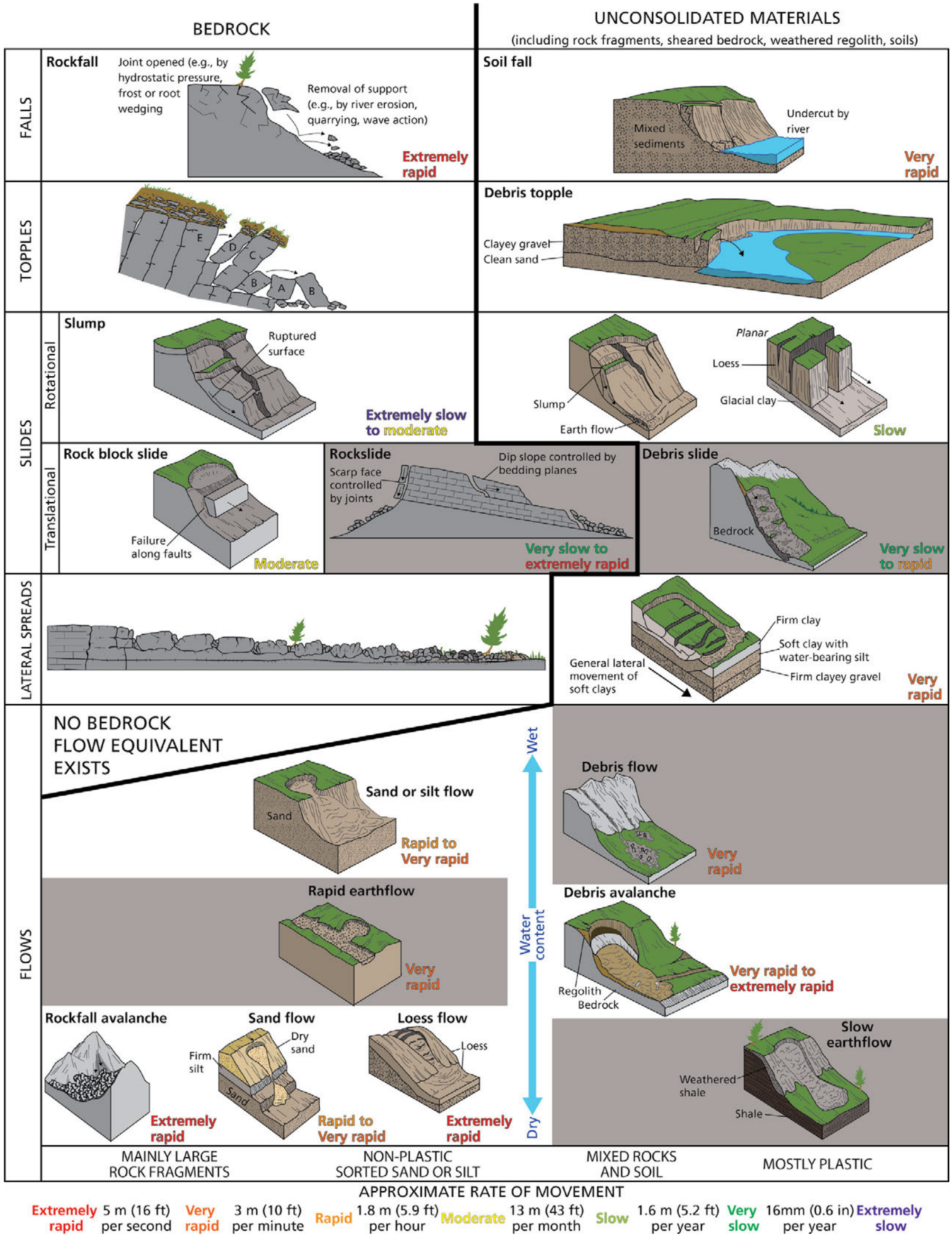

Figure 19. Diagram of different types of slope movements.
As shown in the geohazards GRI GIS data, four types of slope movements occur in the Redwood Creek watershed. From most common to least common, these are debris slides (85.3%), debris flows (13.4%), earthflows (0.9%), and rockslides (0.4%). These types are indicated by gray shading on the figure. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Varnes (1978, figure 4.33 and information therein).

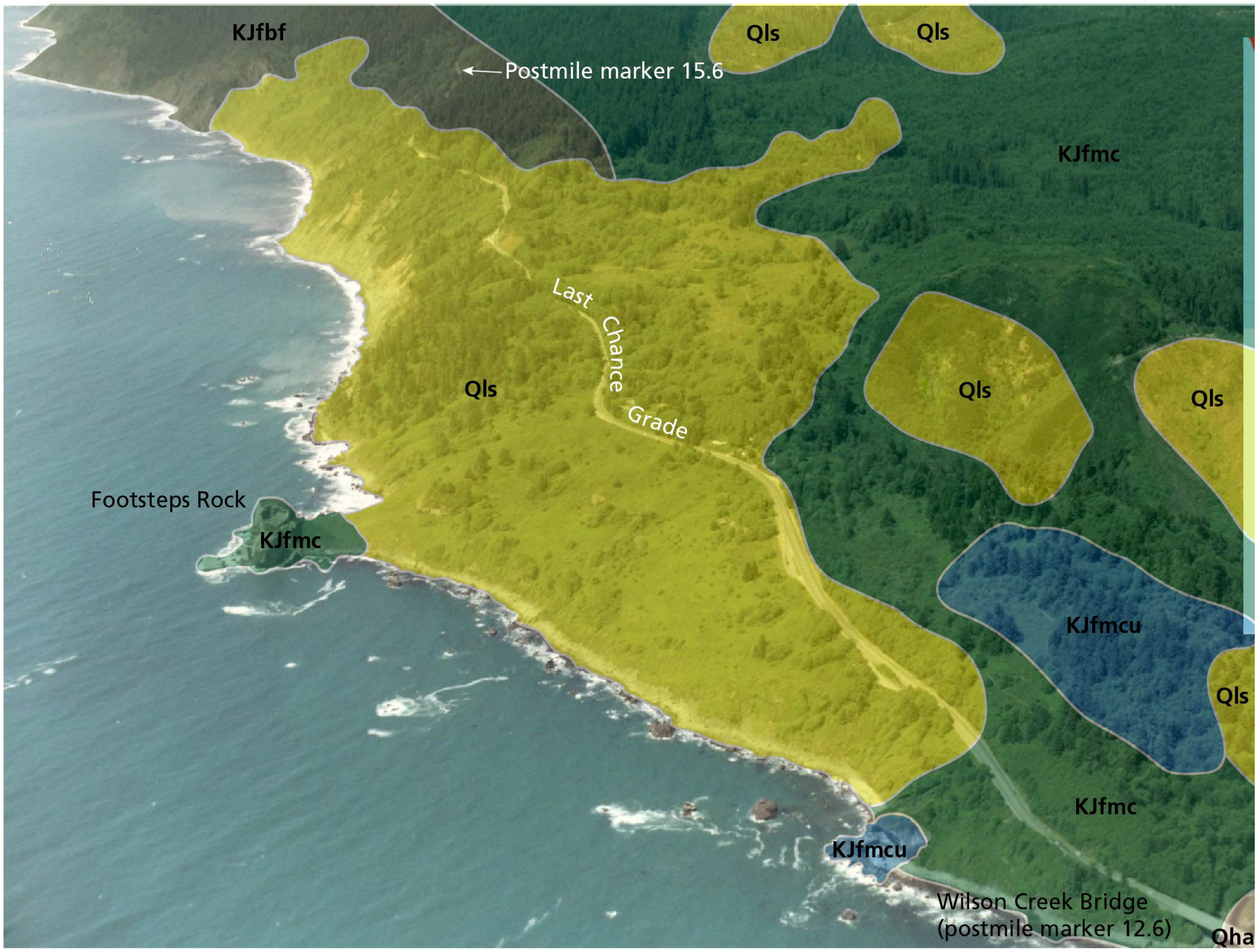

Figure 20. Aerial photograph and geology of Last Chance Grade.
Last Chance Grade is a 5 km (3 mi) segment of Highway 101. At a scale of 1:100,000, Delattre and Rosinski (2012) mapped the length of Last Chance Grade as landslide deposit (Qls). Bedrock underlying Last Chance Grade is Franciscan Complex broken formation (KJfbf; north end) and Franciscan Complex mélange unit of Crescent City area (KJfmc; south end). Unit KJfmcu is part of the mélange but was mapped as an "undifferentiated" ("u") rock mass because its lithology was not confirmed in the field. The characteristic landslide type of the broken formation is rockslide (intact block that slides downhill). The characteristic landslide type of the mélange is earthflow (movement resembles the flow of a viscous liquid). Traveling north from the Wilson Creek Bridge (postmile marker 12.6) to postmile marker 15.6, Last Chance Grade crosses an earthflow complex above Footsteps Rock then crosses into more resistant bedrock characterized by deep-seated rockslides and surficial debris slides. Graphic by Trista Thornberry-Ehrlich (Colorado State University) using California Geological Survey photograph in Wills (2000, figure 2) and GRI GIS data (Delattre and Rosinski 2012).

As mapped by Delattre and Rosinski (2012), Last Chance Grade crosses landslide deposits (**Qls**). The California Department of Transportation (Caltrans) has identified these deposits as composing two primary features: (1) Last Chance Grade (LCG) landslide and (2) Wilson Creek Wall landslide. Both these landslide features are within the Franciscan Complex broken formation (**KJfbf**) and are of the rockslide type (see fig. 19). The broken formation can be thought of as a mass of hard sandstone blocks separated by shear zones (Wills 2000). South of the Wilson Creek Wall landslide, the roadway traverses a large active earthflow (see fig. 19) within the Franciscan Complex mélange unit of Crescent City area (**KJfmc**). Mélange can be thought of as a large shear zone containing relatively few intact blocks (Wills 2000).

Originally constructed in 1937, the roadway on Last Chance Grade has moved 15 m (50 ft) outward as a result of landsliding and erosion at the toe (downslope edge) of the slope. Erosion is caused by tidal activity at the base of Wilson Creek bluffs (at the outer edge of the roadway). This historic and continuous movement equates to a rate of about 19 cm (7.5 in) per year, though the recent rate of movement at this location averages approximately 43 cm (17 in) per year (California Department of Transportation 2016).

In 2018, the State of California approved and funded the Last Chance Grade Project, and Caltrans District 1 (Eureka, California) and its partners initiated the California Environmental Quality Act (CEQA)–National Environmental Protection Act (NEPA) process. CEQA applies to state and local government–proposed actions whereas NEPA applies to federal proposed actions. Both processes promote informed decision making by requiring an environmental review (i.e., analyses and documentation) before making a final decision about whether and how to proceed. The process considers alternatives that would provide more reliable connections through the region; protect economic, environmental, and cultural resources; and reduce maintenance costs (California Department of Transportation 2019). Partners in the process include the National Park Service, California Department of Parks and Recreation, Green Diamond Resource Company, Elk Valley Rancheria, Resighini Rancheria, the Tolowa Dee-ni' Nation, and the Yurok Tribe.

Between 2018 and 2026, the following studies have or will take place at Last Chance Grade: ground surveys, botanical studies, geotechnical investigations, wetland delineations, biological assessment and biological opinion by the US Fish and Wildlife Service, biological assessment and biological opinion by the National Marine Fisheries Service, traffic studies, and CEQA/NEPA public workshops and comment period. The design and permitting phase will take place between 2026 and 2031. Construction is anticipated to begin in 2031 and continue through 2039. The new alternative route will open to the public in 2039 (California Department of Transportation 2017).

If a road failure takes place before the new alternative route is completed, an emergency contract to construct a large roadway retreat or realignment of the roadway around the landslide will be required. The emergency roadway retreat is not likely to be a supported alternative given the associated removal of as many as 200 old-growth redwood trees (California Department of Transportation 2016).

Marijuana Cultivation Sites

The State of California legalized marijuana (*Cannabis sativa*) for medical use in 1996 and for recreational use in 2016. Under the 2016 law, adult (minimum age 21) Californians can grow as many as six plants at home. Cities can prohibit outdoor growing but not indoor growing. Outside of their homes, adults can carry no more than 28.5 g (1.0 oz).

Before 2016, the National Park Service in California—including, in alphabetical order, staff from Point Reyes National Seashore, Redwood National Park, Santa Monica Mountains National Recreation Area, Sequoia Kings Canyon National Park, Whiskeytown National Recreation Area, and Yosemite National Park—had to contend with issues related to the illegal cultivation of marijuana within and around park boundaries (National Park Service 2010). A plethora of law enforcement, visitor safety, and resource (both cultural and natural) management issues were associated with marijuana cultivation. In Whiskeytown National Recreation Area, for example, the cultivation of marijuana was a law enforcement and visitor safety issue because drug trafficking organizations from Mexico were the primary cultivators of these sites. Illegal cultivation sites in the national recreation area had impacts such as land clearing, logging, camping, poaching, and the operation of non-authorized off-road vehicles on abandoned logging and mining roads (National Park Service 2010). Furthermore, illegal marijuana cultivation sites required costly cleanup done by hand with helicopter assistance. Cleanup commonly yielded thousands of marijuana plants; guns; ammunition; 25-pound bags of fertilizers and herbicides; thousands of feet of irrigation hose; hundreds of pounds of trash, including home appliances, hazardous waste, and landscape cuttings; clothing; camping equipment; and food used to support cultivation activities (Weatherbee and Rasmussen 2006).

Although legalization of marijuana has changed some of the issues for the National Park Service in California, park managers still must address the transportation of marijuana through parks. Moreover, although legal cultivation sites are coming under strict guidelines, illegal cultivation continues because of demand in other states (Vicki Ozaki, Redwood National and State Parks, geologist, written communication, 19 August 2020).

The continuing saga of marijuana use and cultivation in California is discussed in this GRI report because of the impacts it has on park resources, including geologic resources. Many legal and illegal marijuana cultivation sites are established in upper Redwood Creek on private land (see Bauer et al. 2015).

The environmental impacts associated with marijuana cultivation appear substantial yet have been difficult to quantify in part because cultivation has been clandestine and commonly occurs on private property (Bauer et al. 2015). Nevertheless, law enforcement and wildlife agencies, as well as researchers, have begun to document a broad array of impacts from marijuana-growing practices, including loss and fragmentation of sensitive habitats, mortality of terrestrial wildlife by rodenticide ingestion, human garbage at cultivation sites as an unnatural food source for wildlife, and algal blooms in lakes and ponds as a result of fertilizers (Milestone 2006; National Park Service 2010; Bauer et al. 2015 and references therein).

Potential impacts of marijuana cultivation on geologic resources include the following:

- Diversion of streamflow. Marijuana is a high water-use plant (Cervantes 2006), consuming an estimated 22.7 L (6.0 gal) of water per day (Bauer et al. 2015). For comparison, widely cultivated wine grapes such as cabernet sauvignon, which is grown throughout much of northwestern California, consume approximately 12.6 L (3.3 gal) of water per day (Williams 2001). Water demand for marijuana cultivation has the potential to divert substantial portions of streamflow, with an estimated flow reduction of up to 23% of the annual seven-day low flow in the least impacted of the study watersheds (i.e., upper Redwood Creek) of Bauer et al. (2015). Estimates from the other study watersheds indicate that water demand for marijuana cultivation exceeds streamflow during the low-flow period. In the most impacted study watersheds, diminished streamflow is likely to have lethal effects on state- and federally listed salmon and steelhead trout and cause further decline of sensitive amphibian species (Bauer et al. 2015). Cumulative effects of water diversions on low summer flows from legal and illegal marijuana cultivation sites is unknown.
- Runoff and erosion. Before 2016, the widespread, and largely unregulated development of marijuana cultivation sites resulted in unauthorized road use and construction of roads, land clearing, logging, and social-trail proliferation, all of which cause gravity- and storm-induced erosion and the delivery of sediments (as well as nutrients, petroleum products, and pesticides) to streams. Because marijuana cultivation requires the transportation of large quantities of pesticides, fertilizers, and irrigation equipment, growers commonly sought existing roadways or trails to facilitate the transport of materials. Use of abandoned logging roads, which were neither designed nor maintained with erosion control features, caused gullying and erosion of the road surface (National Park Service 2010). Now that commercial cultivation of marijuana is regulated by the California Department of Food and Agriculture, growers are required to follow regulations, which has the potential to minimize impacts. Nevertheless, old illegal grows are still in operation, though the number, size, and impacts of these grows is unquantified (Vicki Ozaki, Redwood National and State Parks, geologist, written communication, 19 August 2020).
- Water pollution. Poor water quality is a consequence of the large quantities of chemicals (pesticides, herbicides, and fertilizers) applied to marijuana plants. Some pesticides attach to sediment and are transported into streams. At present, these impacts to the aquatic ecosystem are unquantified and unknown (Vicki Ozaki, Redwood National and State Parks, geologist, written communication, 19 August 2020). Park managers are encouraged to contact the NPS Water Resources Division for assistance with water quality-related issues (see “Guidance for Resource Management”).
- Impacts to soils. Regulation of commercial marijuana cultivation has the potential to minimize many of the following impacts that took place at illegal operations. Before regulation began, illicit marijuana cultivation was extremely destructive to soil profiles in remote areas. Operation of unauthorized off-road vehicles on abandoned logging roads negatively impacted soils. Moreover, camps created for marijuana cultivation were commonly on steep slopes with shallow soil horizons. Growers dug deep benches into the hillside to support camps and provide level ground for sleeping and cooking. Large networks of social trails were developed leading from the camps to the cultivation sites, disturbing soil profiles and increasing erosion. Thousands of holes were dug for planting at cultivation sites, which disrupted the soil profile and increased erosion. Large quantities of fertilizer and pesticides were stored and used at these sites, potentially contaminating soil (National Park Service 2010). Consideration of these issues is still pertinent for minimizing impacts at legal cultivation sites.
- Grading and burying stream channels. Regulation of commercial marijuana cultivation has the potential to minimize many of the following impacts that took place at illegal operations. Before 2016, marijuana growers would store water behind earthen dams, which they constructed by removing soil and placing it in creeks. This practice disrupted streamflow and increased erosion at borrow sites and dam locations. Also, soil was dumped into stream channels during the construction of roads leading to cultivation sites; this was a similar practice to that used during the

construction of logging roads, but unlike timber harvest plans, illegal marijuana cultivation sites had no associated guidance, planning, regulation, or enforcement.

Offshore Geologic Resource Management

The need for comprehensive scientific information about offshore resources, including land and soils (see "Guidance for Resource Management"), is increasingly recognized by researchers, policy makers, and resource managers at all levels (National Research Council 2004; Watkins et al. 2004; The White House Council on Environmental Quality 2009). Maps of offshore areas serve a variety of uses: defining habitats for ecosystem-based management; establishing baselines for long-term monitoring of coastal evolution related to climate change, large storms, and anthropogenic influences; enabling modeling of coastal flooding from sea-level rise and large storms; identifying offshore active faults and submarine landslides, thus providing the basis for earthquake and tsunami hazard assessments and hazard mitigation; providing a database of sediment distribution and thickness, which is important for regional sediment management; enabling more effective regulation of offshore development; improving maritime safety; providing a framework for scientific research; and facilitating outreach to heighten public awareness of coastal and marine ecosystems, resources, and issues (US Geological Survey 2020).

Although park managers and local tribes have been working to identify cultural resources in the area, including the parks' shore and estuaries, the offshore areas of the parks have not been examined in detail to determine if, and where, submerged cultural resources may be located (Borgeld et al. 2007). Notably, cultural studies can lead to information about natural, including geologic, resources (e.g., see "Tsunami Deposits"), but a natural-resource or geologic-resource focus is not known to be part of this NPS–tribal project.

An assessment of coastal and marine resources at the parks (Borgeld et al. 2007) recommended that resource managers prioritize the development of detailed habitat maps of the parks' entire coast. Such maps delineate geomorphology (landforms) and habitat types. Without detailed maps, using data from existing studies is difficult for anything more than managing the study sites themselves. Habitat mapping and geomorphological descriptions would allow managers to scale up, by applying what is known about a few sites to other areas of coast sharing the same characteristics.

In fall 2020, the National Park Service initiated benthic habitat mapping for the 88 coastal, ocean, and Great Lake parks in the National Park System. The project is managed by the Ocean and Coastal Resources Program (OCRP; see "Guidance for Resource Management"). At present only topobathymetric lidar (not benthic habitat) data are available for the parks, but the parks are included in the NPS effort to receive benthic habitat mapping (Monique LaFrance Bartley, Ocean and Coastal Resources Program, marine ecologist, email communication, 6 January 2021).

Two other OCRP projects—sediment and shoreline management and sea level rise—also may be relevant to resource management at the parks. Information about these projects is available at the internal Coastal and Ocean Advisory & Support Team (COAST) SharePoint site (available on NPS computers only).

Quaternary Faults and Earthquakes

The GRI GIS data show numerous named and unnamed faults in the parks. Notably, however, these data show only the onshore segments of these faults, so park managers are directed to the USGS online map viewer, which includes both onshore and offshore Quaternary faults (see "Guidance for Resource Management").

Geologists focus their studies on active faults, that is, faults that have moved during the Quaternary Period (the past 2.6 million years) because movement, which causes earthquakes, is more likely to take place along these faults than on older faults. Faults that have moved during the Holocene Epoch (the past 11,700 years) are considered the most active and dangerous faults (Graymer et al. 2006). The faults in the parks—including the Surpur Creek fault, Lost Man fault, Bald Mountain–Big Lagoon fault, and Grogan fault zone—are active (fig. 21).

Most earthquake damage is caused by shaking, which can bring down poorly built structures and dislodge interior furniture and housewares, resulting in injuries. More dramatic damage includes collapsed roads and bridges, release of hazardous materials, and destructive fires. Associated geologic hazards include tsunamis (see "Tsunamis"), landslides (see "Landslides"), ground rupture (visible breaking [cracks] and displacement in Earth's surface), and liquefaction (transformation of loosely packed sediment into a more tightly packed fluid mass, which may cause failure of built structures).

A large earthquake could drastically change the parks' coast: some coastal areas may subside while others may uplift. In 1992, the magnitude (M) 7 Cape Mendocino earthquake uplifted about 16 km (10 mi) of the coast near Petrolia, California, as much as 1.5 m (5 ft), which stranded intertidal communities above the intertidal zone, resulting in their demise (fig. 22).

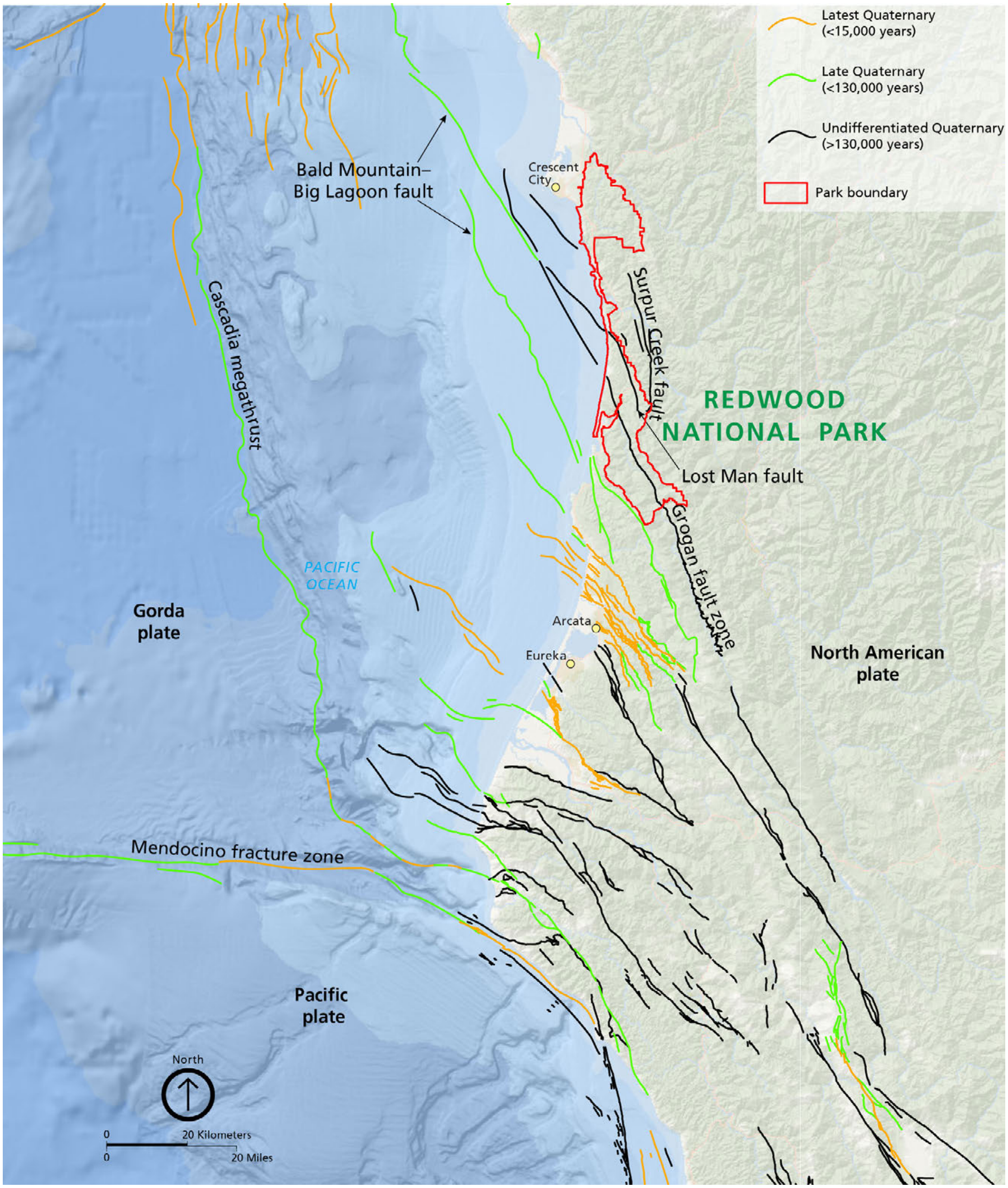

Figure 21. Map of Quaternary faults.
The parks and surrounding area are replete with coastal onshore and offshore faults. The faults on this figure are from the USGS Quaternary faults database (US Geological Survey 2021). All these faults are considered active, including the Surpur Creek, Lost Man, and Grogan faults, which cut through the parks. Some faults mark major plate boundaries; the Cascadia megathrust, for example, marks where the Gorda plate is subducting beneath the North American plate at the Cascadia subduction zone. The Mendocino fracture zone marks where the Gorda and Pacific plates are sliding past each (see fig. 8 for relative plate motions and other plate tectonic features). Graphic by Trista Thornberry-Ehrlich (Colorado State University). Base imagery is ESRI ArcGIS World Imagery.

Figure 22. Photograph of uplifted tidepools at Cape Mendocino.
In 1992, rocky coastal areas that had been submerged below the Pacific Ocean were uplifted—as much as 2 m (6 ft) locally—during the M 7.2 Cape Mendocino earthquake. Sudden coastal uplift caused the death of many marine organisms. Residents of the area noticed the smell of dying sea creatures within days of the event. NPS photograph from Natoli and Lillie (2006, figure 4.8).

The primary source of earthquakes to the north coast of California is the Cascadia subduction zone. The fault at the surface of the subduction zone is referred to as the Cascadia "megathrust" (see fig. 21) and marks the nearly 1,100-km- (700-mi-) long plate boundary where the Juan de Fuca and Gorda plates are subducting beneath the North American plate (see fig. 8).

Subduction leads to active compressional tectonics and uplift (Wills 2000). The M 9 Cascadia earthquake in 1700 CE (see "Tsunami Deposits") likely ruptured the entire length of the fault from Cape Mendocino, California, to Vancouver Island, British Columbia (Dengler et al. 2016). The larger a rupture area, the larger an earthquake. A M 9 earthquake along the Cascadia megathrust would cause immense shaking, lasting an estimated 2–4 minutes, and liquefaction. It would trigger landslides from northern California to British Columbia as well as tsunamis (see "Tsunamis").

Other sources of earthquakes to the north coast of California include coastal and offshore faults (see fig. 21), the Mendocino fracture zone (see fig. 21), the Mendocino triple junction (see figs. 8 and 21), the San Andreas Fault system (the transform plate boundary south of the Mendocino triple junction; see fig. 8), the Modoc Plateau (a region of active volcanism and faults in the northeastern part of California), and faults in the Basin and Range (Clarke 1992; Clarke and Carver 1992; Fuller 2015; Dengler et al. 2016). The Basin and Range is a sprawling region of active faults resulting from extension (pulling apart of Earth's crust); the western edge of the Basin and Range is located at the foot of the Sierra Nevada in California.

Redwood Creek and the Clean Water Act

Due to excessive sediment and elevated temperatures, Redwood Creek is on the federal list of impaired water bodies under section 303(d) of the Clean Water Act (California Environmental Protection Agency 2019). Impairment is the result of the following key changes that have taken place in the mainstem of Redwood Creek: (1) increases in the volume of stored sediment, (2) decreases in pool numbers and depth, (3) increases in stream width and decreases in stream depth, (4) reduced volumes and recruitment of large woody debris, and (5) deposition of high levels of fine sediments on the stream bottom (US Environmental Protection Agency 1998). Excessive sediment and elevated temperatures impair beneficial uses of stream water for significant purposes, specifically those associated with salmon and steelhead trout (North Coast Regional Water Quality Control Board 2015).

Three fish species that inhabit Redwood Creek are listed by the Endangered Species Act. These threatened species are coho salmon (*Oncorhynchus kisutch*), steelhead trout (i.e., the anadromous form of rainbow trout, *Oncorhynchus mykiss*), and chinook salmon (*Oncorhynchus tshawytscha*). Coho salmon is also listed as threatened by the state. Preventing the extinction of these species means restoring many key habitat attributes that are in poor condition in the Redwood Creek watershed (US Environmental Protection Agency 1998).

Stream Sediment

Sediment source inventories showed that landslides, stream diversions, and gullies were the largest contributors of sediment to Redwood Creek, and many of these features were associated with roads (Madej 2021). Consequently, the focus of the parks' watershed restoration program became the removal of abandoned forest roads and upgrading drivable roads (see "Restoration of Redwood Creek Watershed").

The National Park Service contracts with the US Geological Survey to measure suspended sediment at the Redwood Creek gaging station in Orick. Park staff operates three gaging stations in Prairie Creek, which is a tributary to Redwood Creek. The Prairie Creek stations provide streamflow and sediment monitoring of two pristine old-growth redwood forests and one restored watershed in which roads have been removed and second-growth forest has been thinned (see "Restoration of Redwood Creek Watershed"). As such, these stations provide a rare data set of hydrology and sediment transport in an old-growth redwood forest. This type of data provides a valuable comparison to managed watersheds in coastal northern California. Long-term records at these gaging stations will help determine shifts or changes in the timing and magnitude of winter flows, and the timing and magnitude of base flows (Vicki Ozaki, Redwood National and State Parks, geologist, written communication, 20 August 2020).

Stream Temperature

Temperature is a master environmental variable in stream ecosystems. Low flows make streams prone to excessive heating (Janda et al. 1975). Ecosystem processes such as decomposition, primary production, community respiration, and nutrient cycling are all temperature dependent. In addition, the metabolism, growth, life cycles, and overall productivities of populations of most stream organisms are temperature dependent.

Water temperature influences many aspects of a salmon's life cycle, including egg development, juvenile appetite and growth, migration, and distribution (Wiltzbach and Ozaki 2017). Juvenile coho salmon and steelhead trout, which reside in Redwood Creek for at least one year, prefer temperatures between 12°C and 14°C (54°F and 57°F). At about 18°C–20°C (64°F–68°F), growth stops or slows down. Extended exposure above 25°C (77°F) may be lethal (Ozaki 2014).

Unlike many rivers that get warmer as they flow downstream, Redwood Creek reaches its maximum temperature in the middle basin. A wide river valley with floodplains, channel widening, sediment accumulation, and reduced shading contribute to the warm temperatures. In the middle basin, the seven-day average daily maximum temperature (called the "maximum weekly maximum temperature" [MWMT]) frequently reaches 27°C (80°F; Welsh et al. 2001). Consequently, several juvenile fish kills have been observed in this reach of the creek (Vicki Ozaki, Redwood National and State Parks, geologist, written communication, 19 August 2020).

Redwood Creek becomes cooler farther downstream, where coastal fog, shading by old-growth redwood trees in the riparian zone, and the presence of cold springs contribute to the cooling trend. Maximum water temperature in lower Redwood Creek on foggy days is 2°C–3°C (4°F–5°F) cooler than on sunny days. Nevertheless, MWMTs range from 20°C (68°F) to 23°C (74°F), which is still higher than the preferred temperature for coho (Madej 2021). In the reaches below the Tall Trees Grove, cold pools have been mapped along the mainstem of Redwood Creek. Although few, these pools are often isolated from the mainstem by a gravel bar and open on the downstream end. They provide waters as much as 3°C–9°C (5°F–16°F) cooler than the mainstem (Ozaki 1988; Nielsen et al 1994).

In contrast to Redwood Creek, water temperature in Prairie Creek—a tributary to Redwood Creek—is at present fully suitable throughout the year to support production of salmonids (i.e., Chinook salmon, coho salmon, and steelhead trout) and other cold-water fishes (Wiltzbach and Ozaki 2017). Mill Creek—a tributary of the Smith River—also has suitable water temperature to support healthy populations of coho (Vicki Ozaki, Redwood National and State Parks, geologist, written communication, 20 August 2020).

Redwood Creek Streamflow

High flood flows and prolonged low flows are part of the natural flow regime of Redwood Creek. Nevertheless, both extremes are sources of environmental concern.

High flood flows drastically rearrange stream channels and riparian hillslopes, transport enormous quantities of sediment, and damage infrastructure and esthetic values (Janda et al. 1975). Five peak flows of around 50,000 cfs occurred in 1953, 1955, 1964, 1972, and 1975 (see fig. 5). Between 1976 and 2020, only four peak flows (1986, 1995, 1998, and 2005) exceeded 30,000 cfs. Whether this decrease in high flood flows is a natural, decadal-scale fluctuation, or a result of climate change, is unknown.

Low flows of summer greatly restrict the living area available to aquatic organisms. Without continuous flow, pools become isolated pockets of warm stagnant water. Juvenile salmon and steelhead, as well as other aquatic species, become stranded in these pools and are subjected to poor water quality and increased predation from birds, raccoons, and other animals as they are concentrated into smaller and shallower pools (Madej 2021) until the pools ultimately dry up and all aquatic species perish (Vicki Ozaki, Redwood National and State Parks, geologist, written communication, 19 August 2020).

The lower Redwood Creek has gone dry at least four times since 2002. The channel typically starts to become disconnected in late summer and the dry channel has extended from Prairie Creek upstream as far as 2.4 km (1.5 mi; Vicki Ozaki, Redwood National and State Parks, geologist, written communication, 19 August 2020).

Although a water budget analysis is needed to determine the causes (Mary Ann Madej, US Geological Survey, emeritus geologist, email communication, 15 November 2019), several factors likely contribute to summer low flows: second-growth forests are becoming more prevalent as clear-cut hillslopes revegetate, which increase water demand; sand and gravel accumulation in the channel bed allows more streamflow to go subsurface; legal and illegal water diversions for residential and agricultural use have increased; and a trend of higher air temperature and possible decrease in fog increases evapotranspiration demands (Madej 2021).

Restoration of Redwood Creek Watershed

Restoration is a key issue at the parks and part of its purpose (National Park Service 2016a). Redwood National Park was established in 1968 and then expanded in 1978 to better protect old-growth redwood trees from excessive erosion and sedimentation, resulting from timber harvest, associated road construction, and large floods.

Most of the Redwood National Park expansion area, the entire Mill Creek watershed in Del Norte Coast Redwoods State Park, and other areas now in the parks were heavily impacted by logging (see fig. 4). The Redwood National Park expansion area had been tractor logged, which resulted in an extensive network of unpaved logging haul roads (more than 670 km [415 mi]) and skid roads (an estimated 4,800 km [3,000 mi]). Most of these roads were built before the establishment of the California Forest Practice Rules, which implement a suite of acts that address timber harvest in the state.

As part of the 1978 legislation, Congress instructed the National Park Service to “conduct erosion and sedimentation studies in the Redwood Creek basin.” This unique congressional mandate led to the establishment of a federal scientific team to examine geomorphic processes that might affect the health of the coast redwood ecosystem. Initially, studies focused on the identification and assessment of sediment sources and causes of hillslope erosion, tracking the movement and storage of sediment resulting from such erosion, and quantifying the amount of sediment flushed out of the watershed by Redwood Creek (Madej 2021).

Like the initial research focus on sedimentation, restoration focused on the removal of logging roads because a large proportion of observed erosion was associated with the extensive road network (Kelsey et al. 1981; Hagans and Weaver 1987; Best 1995; US Environmental Protection Agency 1998). Since 1978, the National Park Service has decommissioned about 410 km (255 mi) of abandoned logging roads and moved an estimated 3.7 million m^3 (4.8 million yds^3) of material from unstable locations to more stable sites (Madej 2021). Decommissioning involves clearing stream channels choked with road fill and logging debris, recontouring hillslopes marred by road networks, and reestablishing natural drainage patterns, which is accomplished using large, heavy equipment, primarily bulldozers and excavators (fig. 23).

Figure 23. Photograph of restoration activity along Lost Man Creek.
In the Redwood Creek watershed, Lost Man Creek flows into Prairie Creek, which flows into Redwood Creek. The Franciscan Complex coherent unit of Lacks Creek (KJfl) underlies the Lost Man Creek basin. Like restoration activities elsewhere in the parks, road removal here required the use of heavy equipment to excavate stream-crossing fill material, restore channels close to their original configuration, and place excavated fill in stable locations to best mimic pre-disturbance topography and drainage patterns. Photograph by Katie KellerLynn (Colorado State University), taken 8 October 2019.

Removal of logging roads, revegetation of hill slopes, and improvements in timber-harvest practices have led to decreased sediment yields from 1975 levels. As evidenced by a 10-year storm in 1997, abandoned logging roads that had been restored exhibited less than one-third the erosion of untreated roads (Madej 2021). This is a "cautionary tale," however, because today's restored landscape in the parks has yet to be tested by a storm as intense as those common from 1953 to 1975 (see fig. 5). The last big storm was the 1997 storm, which set back channel recovery to conditions found in the early 1980s. By 2007, pools had not recovered to conditions prior to the 1997 flood (Vicki Ozaki, Redwood National and State Parks, geologist, written communication, 19 August 2020).

While great strides have been made toward restoration, significant areas of degraded watersheds, forests, and streams still require restoration to conditions where slopes are stabilized, forests attain old-growth characteristics, lands and waters support resilient animal and plant communities, and prioritized sediment risks are reduced (National Park Service 2016a). Prioritized sediment risks are measured by total maximum daily load (TMDL) and call for a 60% reduction in sediment discharge in Redwood Creek. Since implementation of the TMDL in 1998, 40% of the required sediment load reductions have been attained (North Coast Regional Water Quality Control Board 2015).

To address the complexity and breadth of restoration, collaborative partnerships have been an ongoing strategy at the parks. In 2004, a collaborative partnership of private landowners, non-profit organizations, and agencies (including Redwood National and State Parks) with scientific or regulatory interests established the Redwood Creek Watershed Group. The group developed the "Redwood Creek Integrated Watershed Strategy" (Redwood Creek Watershed Group 2006) as a guideline to restore and protect the beneficial uses of the watershed. More recently, in 2018, the National Park Service, California State Parks, and Save the Redwoods League created "Redwoods Rising," which is a massive, collaborative restoration effort to improve forest and watershed conditions and connectivity across the 49,000 ha (120,000 ac) of forests in the parks.

Work efforts of Redwood Rising, which are expected to continue for the next decade or more, will concentrate on second growth forest restoration (thinning), road removal, and aquatic and riparian restoration (e.g., adding large woody debris; see "Stream Processes and Coast Redwoods"). The first two main project areas are 12,280 ha (30,350 ac) in the greater Mill Creek watershed and 3,600 ha (9,000 ac) in the greater Prairie Creek watershed (Redwood National and State Parks 2019). As part of Redwood Rising, park staff will be monitoring turbidity (as a surrogate for suspended sediment) in Prairie Creek and suspended sediment in Mill Creek (Vicki Ozaki, Redwood National and State Parks, geologist, written communication, 20 August 2020).

The results of Redwood Rising have geologic applications. For example, the Mill Creek and Prairie Creek watersheds have different underlying geology. The Franciscan Complex broken formation (**KJfbf**) underlies the Mill Creek watershed. The Prairie Creek Formation (**QTpc**) underlies the Prairie Creek watershed. Studying post-restoration effectiveness will be illuminating with respect to geomorphic processes operating in these different geologic contexts (GRI conference call, 18 November 2019).

Restoration of Redwood Creek Estuary

Along with the removal of legacy logging roads and management of second-growth forests, improving habitat in the Redwood Creek estuary is part of the overall restoration of the Redwood Creek watershed. The estuary provides critically important rearing habitat for commercially valuable and federally listed threatened salmonids.

Historically, the Redwood Creek estuary was quite different from its current condition. Agricultural pastures and other private lands now occupy areas that once contained sloughs (sluggish channels of water or marshy areas), high-flow channels, and a dense riparian floodplain forest, which were key elements that contributed to the biological functioning of the estuary (Ricks 1995). Changes to the landscape, including removal of spruce trees and other vegetation, allowed farming and grazing of the rich alluvial soils and intermixed wetland area but degraded estuary function (Hofstra 1983).

Another significant change was a federal flood control project. Following damaging floods in 1953, 1955, and 1964 (see fig. 5), concern for flood protection of the community of Orick and surrounding development prompted the US Army Corps of Engineers to build flood-control levees (Hofstra 1983; Larson 1987; Ricks 1995). Constructed from 1966 to 1968, the levees channelized the lower reach of Redwood Creek and cut off the last downstream meander (fig. 24). With streamflow confined within the levees, hydrologic processes in the estuary changed and sediments deposited in the south slough and the north slough were no longer flushed from the mouth of Redwood Creek. As a result, half of the lower estuary filled with sediment or became isolated from the embayment (the relatively deep, broad part of the mouth landward from the beach). Thereby, the flood control project impacts the biological and physical functioning of the estuary by eliminating deep-water pools and natural water circulation patterns, disrupting sediment transport processes, and significantly reducing the overall size of the tidal prism, estuary, and lagoon (Ricks 1995).

Presently, park managers are working with partners (local landowners and local, state, and federal agencies) to identify restoration options that would restore estuary function while preserving the benefit of flood protection (National Park Service 2016a). Any proposed restoration project would benefit from a review of previous work, which is ample. A quick search of the NPS Integrated Resource Management Applications (IRMA) data store yielded 54 records pertaining to restoration of the Redwood Creek estuary. Dates of these records range from 1980 to 2016 and include published and unpublished reports, a presentation, a watershed strategy, monitoring data, and theses. In addition, the Redwood Creek Watershed Group (2006) proposed a strategy and documented this issue; the strategy is applicable to future restoration.

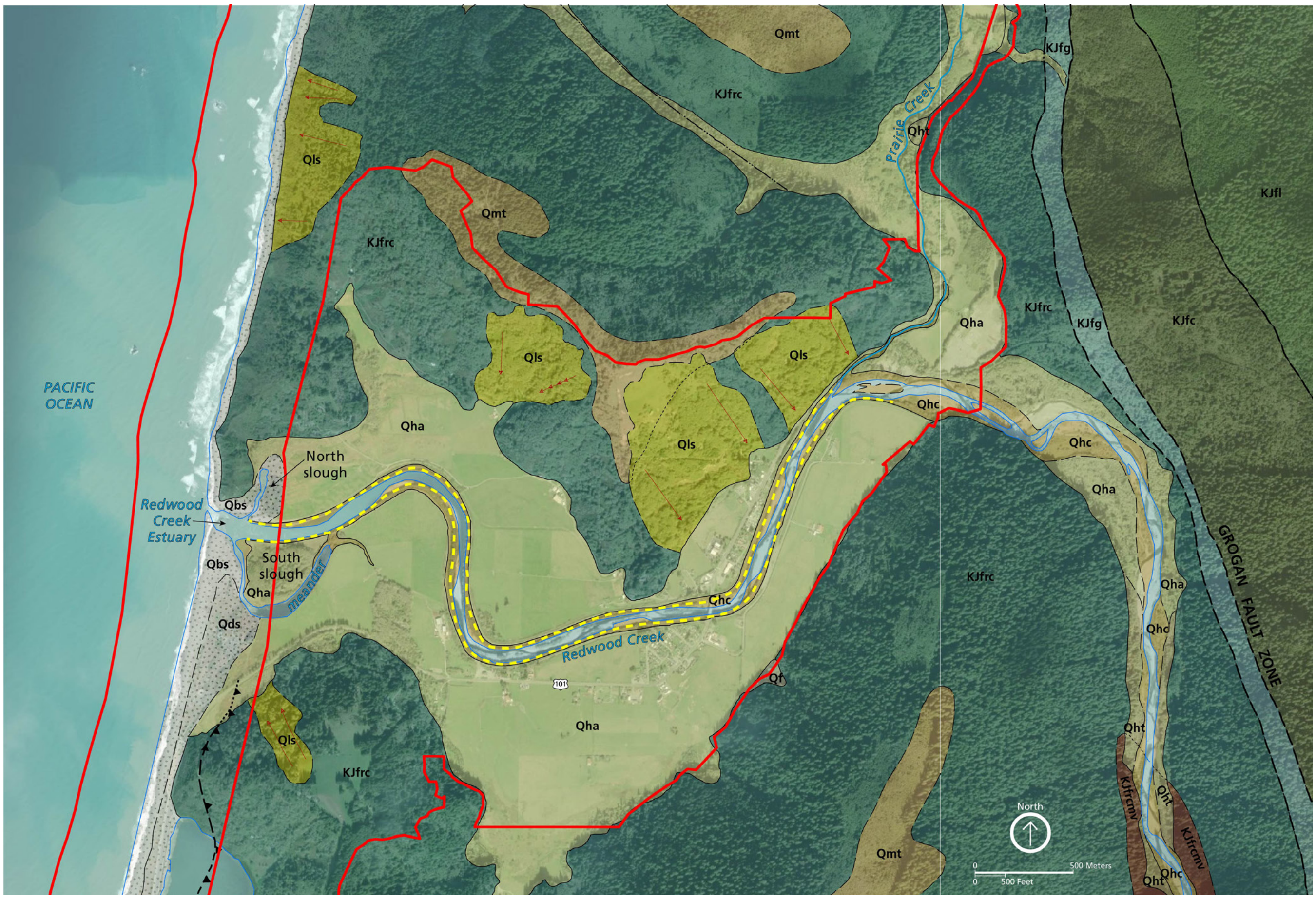

Figure 24. Aerial image and geology of lower Redwood Creek and estuary.
Levee construction in 1968 changed the morphology of the lower Redwood Creek and estuary. The creek and estuary are now divided into four distinct areas that differ physically and chemically: Redwood Creek estuary, Redwood Creek above the estuary, south slough, and north slough. Starting near the confluence with Prairie Creek, the US Army Corps of Engineers built levees (dashed yellow lines on the figure) that followed the original course of Redwood Creek. The final 1.0 km (0.6 mi) of levee cut off the last meander (on the south side of south slough) of the original creek course and aimed the creek flow directly out to sea. See table 3 for a listing of map units. Graphic by Trista Thornberry-Ehrlich using GRI GIS data and base imagery from ESRI ArcGIS World Imagery.

Tsunamis

The parks are situated along the north coast of California, which is the most tsunami-prone area of the continental United States. In the past 70 years, 34 tsunamis have inundated the coast; five caused damage (Humboldt State University 2019).

Locations of greatest risk for tsunamis are beaches and low-lying coastal areas. Tsunamis may reach heights of 6 to 15 m (20 to 50 ft) along the coast and, in isolated areas, even higher. Only in large coastal rivers is a tsunami surge likely to penetrate farther than 3 km (2 mi) inland (Dengler et al. 2016).

Tsunamis are tricky. The first sign of a tsunami may not be a large wave but an unusual lowering and receding of ocean water, exposing the seafloor. Another natural warning sign may be a loud roar from the ocean. Tsunamis may look like sloping mountains of water or rush ashore like a flooded river choked with debris. The first tsunami surge is not necessarily the highest. In northern California, the largest surge may occur hours after the initial wave and be amplified by high tides. The time between surges may range from minutes to hours. A tsunami event lasting 12 hours is not unusual, and some last much longer. Also, "just when you think it is all over, another very large surge may come" (National Oceanic and Atmospheric Administration et al. publication date unknown, page number undesignated). Predicting how many surges or how much time will elapse between waves is not possible (Dengler et al. 2016).

The most notable and damaging tsunami in recent California history took place in 1964. The M 9.2 Alaska earthquake, which was the largest earthquake ever recorded in North America (Natoli and Lillie 2006), produced a tsunami that flooded 29 blocks of Crescent City's waterfront, damaged harbors and port facilities as far south as Santa Cruz, California, and caused 12 deaths in the north coast area (Dengler et al. 2016).

Tsunamis in California have three potential sources—local, near-field, and far-field. Local tsunamis are generated by submarine landslides (McCulloch 1985; Ryan et al. 2012). Near-field tsunamis are associated with earthquakes on the Cascadia subduction zone/megathrust (Wilson et al. 2010; Barberopoulou et al. 2011). Far-field (also referred to as "distant-source," "transoceanic," or "trans-Pacific") tsunamis originate at other subduction zones around the Pacific Rim (Ross et al. 2013).

Local tsunamis occur with little or no warning. Ground shaking serves as a warning for tsunamis generated on the Cascadia subduction zone. In a far-field tsunami, ground shaking will likely not be felt, but official notification is supplied if evacuation is necessary (Vicki Ozaki, Redwood National and States Parks, geologist, written communication, 19 August 2020).

The United States is served by two tsunami warning centers: The National Tsunami Warning Center serves the continental United States, Alaska, and Canada. The Pacific Tsunami Warning Center directly serves the Hawaiian Islands, the US Pacific and Caribbean territories, and the British Virgin Islands and is the primary international forecast center for the Pacific and Caribbean basins. These centers are operated by NOAA, which has developed transoceanic tsunami buoy systems (see "Guidance for Resource Management").

In the case of a great Cascadia earthquake (M 8.5–9.0) and associated major near-field tsunami with a 15-to-30-minute transit time to the Pacific coastline (Meyers 1994), waiting for an authorized warning would not allow sufficient time to initiate life-saving evacuation. To avert a catastrophe, coastal residents and tourists at the Cascadia margin must evacuate to high ground without delay following an earthquake on the Cascadia subduction zone. The "at risk" populations must not wait for official warnings, directions, or permissions to self-initiate the life-saving evacuations (Peterson et al. 2013). Signs marking "entering" and "leaving" tsunami inundation zones (fig. 25) are posted in the parks.

Staff members at the parks provide visitors with a brochure, *Staying Safe on North Coast Beaches*, which contains guidance for how to stay safe while enjoying the parks' beaches. The brochure also has safety tips about sneaker waves (also called "rogue waves" or "sleeper wave"). These waves are "sneaky" because they usually occur between long periods of calm ocean and run up the beach farther than expected. Other types of beach hazards include rising tides, rip currents (strong, localized, narrow currents of water that move directly away from the shore, cutting through the lines of breaking waves like a river running out to sea), collapse of steep cliffs, and waves that overtop rocks and jetties.

For the past decade, the California Geological Survey (CGS) has worked with the Redwood Coast Tsunami Work Group—a collaboration of many organizations, including NOAA/National Weather Service and

Redwood National and State Parks (see "Guidance of Resource Management")—to develop a protocol for determining the extent of the hazard zone for use in public maps. CGS geologists updated the tsunami hazard maps for Del Norte and Humboldt Counties in 2021. As tsunami hazard maps for counties in California are completed, they are posted at the CGS website (see "Guidance for Resource Management"). The Redwood Coast Tsunami Work Group also posts tsunami maps, informational brochures, and graphics, including tsunami hazard maps for specified cities and locations in Del Norte and Humboldt Counties (see "Guidance for Resource Management").

Figure 25. Photograph of tsunami hazard zone sign. "Entering" and "leaving" signs, as well as tsunami evacuation route signs, are posted in areas identified as being inundated during a tsunami. These signs have been controversial for reasons ranging from cost of replacement (they are the most-stolen signs on the West Coast) to cost of scaring away tourists (Natoli and Lillie 2006), although these tourists (at Shelter Cove, California) do not seem too scared and may simply be happy to leave this tsunami hazard zone. Photograph ("selfie") by David Lynn, taken 10 October 2019.

Guidance for Resource Management

These references, resources, and websites may be of use to resource managers. The laws, regulations, and policies apply to NPS geologic resources. The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (§ 204), National Park Service 2006 Management Policies, and the Natural Resources Inventory and Monitoring Guideline (NPS-75).

Three Basic Ways to Receive Geologic Resource Management Assistance

- Contact the NPS Geologic Resources Division (GRD; https://www.nps.gov/orgs/1088/contactus.htm). GRD staff members provide technical and policy support for geologic resource management issues in three emphasis areas: (1) geologic heritage (e.g., landforms and paleontology), (2) active processes and hazards, and (3) energy and minerals management. GRD staff can provide technical assistance with resource inventories, assessments, and monitoring; impact mitigation, restoration, and adaptation; hazards risk management; law, policy, and guidance; resource management planning; and data and information management. Park managers can formally request assistance via https://irma.nps.gov/Star/.
- Submit a proposal to receive geologic expertise through the Scientists in Parks (SIP) program (see https://www.nps.gov/subjects/science/scientists-in-parks.htm). This program, which was formerly the Geoscientists-in-the-Parks (GIP) program, places scientists (typically undergraduate students) in parks to complete geoscience-related projects that may address resource management issues. The Geological Society of America and Environmental Stewards are partners of the SIP program. GRD staff can provide guidance in submitting a proposal to receive assistance, for example, with research, interpretation and public education, inventory, and/or monitoring.
- Refer to *Geological Monitoring* (Young and Norby 2009), which provides guidance for monitoring vital signs (measurable parameters of the overall condition of natural resources). Each chapter covers a different geologic resource and includes detailed recommendations for resource managers, suggested methods of monitoring, and case studies. Chapters are available online at https://www.nps.gov/subjects/geology/geological-monitoring.htm.

Assistance with Water-Related Issues

Although water is a geologic agent, some water-related issues are best addressed by the NPS Water Resources Division (WRD), rather than the NPS Geologic Resources Division. Such issues include water quality, wetlands, and water rights. Park managers are directed to the WRD website for program specifics (https://home.nps.gov/orgs/1439/index.htm) and contact information (https://home.nps.gov/orgs/1439/contactus.htm). Park managers can formally request assistance from the Water Resources Division via https://irma.nps.gov/Star/.

Assistance with Coastal Issues

The NPS Geologic Resources Division, Coastal Geology Program (https://home.nps.gov/subjects/geology/coastal-geology.htm), and the NPS Water Resources Division, Ocean and Coastal Resources Program (OCRP; https://www.nps.gov/orgs/1439/ocrb.htm), share responsibility for assisting park managers with resource issues in 88 ocean, coastal, and Great Lakes parks. Topics of interest include beaches, dunes, and other coastal landforms; beach materials; coastal processes; engineering in the coastal environments; and coastal hazards.

Park managers may benefit from the following NPS guidance and databases for managing coastal resources, including planning for the impacts of climate change:

- The NPS *Coastal Adaptation Strategies Handbook* (Beavers et al. 2016) provides guidance about climate change adaptation to coastal park managers. Focus topics of the handbook include NPS policies relevant to climate change; guidance on evaluating appropriate adaptation actions; and adaptation opportunities for planning, incident response, cultural resources, natural resources, facilities and assets, and infrastructure. The handbook also provides guidance on developing communication and education materials about climate change impacts and details case studies of the many ways that park managers are implementing adaptation strategies for threatened resources throughout the National Park System.
- The NPS *Ocean and Coastal Park Jurisdiction Handbook* (National Park Service 2016b) guides coastal resource management by providing insight for parks with boundaries that may shift with changing shorelines.
- The NPS *Cultural Resources Climate Change Strategy* (Rockman et al. 2016) connects climate science

with historic preservation planning and is related to coastal resource management and planning. The strategy identifies and describes seven options for climate change adaptation of cultural resources and cultural landscapes: (1) no active intervention, (2) offset stress, (3) improve resilience, (4) manage change, (5) relocate or facilitate movement, (6) document and prepare for loss, and (7) interpret the change.

- The "Coastal Features and Processes" chapter (Bush and Young 2009) of *Geological Monitoring* (Young and Norby 2009) discusses vital signs for monitoring the following coastal features and processes: (1) shoreline change, (2) coastal vegetation cover, (3) wetland position/acreage, and (4) coastal wetland accretion. Since publication of *Geological Monitoring* in 2009, researchers have developed new methodologies for monitoring coastal features and processes; park managers could consider working with partners such as the US Geological Survey to utilize methodologies that reflect new advances and approaches (Jim Flocks, US Geological Survey, coastal geologist, written communication, 13 November 2018). To develop additional monitoring protocols for coastal resources, park managers could potentially work with the Klamath Inventory & Monitoring Network.

Park-Specific Documents

The National Park Service prepares a variety of planning and environmental documents to help guide management of park resources and visitor use. The parks' foundation document (National Park Service 2016a) was used in preparation of this report. Other sources on park-specific information include the following:

- NPS Planning, Environment and Public Comment (PEPC) provides information about park planning: https://parkplanning.nps.gov/parks.cfm
- NPS Technical Information Center (TIC) maintains a repository of technical documents: https://pubs.etic.nps.gov/
- Integrated Resource Management Applications (IRMA) is a repository of park-specific documents: https://irma.nps.gov/DataStore/. Notably, park staff has compiled many data sets and reports about the restoration of watersheds in the parks. References may be found at IRMA by selecting the "Reports" tab then "Featured Content." Select "Redwood National Park" from the dropdown menu under "Select a Park, Office, Program or Region" and, under the "Select Category of Featured Content," select one of the following categories: "Fisheries Collection," "History of Redwood National and State Parks," "Management Plans: Redwood National and State Parks," "Prairie Creek Fisheries Bibliography," "Redwood Creek Estuary," "Research: Second Growth Forest Restoration," "Restoration: Redwood National and State Parks," "Road Removal and Watershed Restoration," "*Sequoia Sempervirens* Collection," and "USGS Redwood Field Station Collection."

NPS Resource Management Guidance and Documents

- 1998 National Parks Omnibus Management Act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf
- NPS-75: Natural Resource Inventory and Monitoring Guideline: https://irma.nps.gov/DataStore/Reference/Profile/622933
- NPS Management Policies 2006 (Chapter 4: Natural Resource Management): https://www.nps.gov/subjects/policy/upload/MP_2006.pdf
- NPS Natural Resource Management Reference Manual #77: https://irma.nps.gov/DataStore/Reference/Profile/572379

Geologic Resource Laws, Regulations, and Policies

The following table (table 6) was developed by the NPS Geologic Resources Division. The table summarizes laws, regulations, and policies that specifically apply to NPS minerals and geologic resources. The table does not include laws of general application (e.g., Clean Water Act, Endangered Species Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available.

Table 6. Geologic resource laws, regulations, and policies.

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

Table 6, continued. Geologic resource laws, regulations, and policies.

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

Table 6, continued. Geologic resource laws, regulations, and policies.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Soils	**Soil and Water Resources Conservation Act, 16 USC §§ 2011–2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources. **Farmland Protection Policy Act, 7 USC § 4201 et. seq.** requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).	**7 CFR Parts 610 and 611** are the US Department of Agriculture regulations for the Natural Resources Conservation Service. **Part 610** governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. **Part 611** governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements.	**Section 4.8.2.4** requires NPS to -prevent unnatural erosion, removal, and contamination; -conduct soil surveys; -minimize unavoidable excavation; and -develop/follow written prescriptions (instructions).
Geothermal	**Geothermal Steam Act of 1970, 30 USC. § 1001 et seq.** as amended in 1988, states -No geothermal leasing is allowed in parks. -"Significant" thermal features exist in 16 park units (the features listed by the NPS at 52 Fed. Reg. 28793-28800 (August 3, 1987), plus the thermal features in Crater Lake, Big Bend, and Lake Mead). -NPS is required to monitor those features. -Based on scientific evidence, Secretary of Interior must protect significant NPS thermal features from leasing effects. **Geothermal Steam Act Amendments of 1988, Public Law 100--443** prohibits geothermal leasing in the Island Park known geothermal resource area near Yellowstone and outside 16 designated NPS units if subsequent geothermal development would significantly adversely affect identified thermal features.		**Section 4.8.2.3** requires NPS to -Preserve/maintain integrity of all thermal resources in parks. -Work closely with outside agencies. -Monitor significant thermal features.

Table 6, continued. Geologic resource laws, regulations, and policies.

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

Table 6, continued. Geologic resource laws, regulations, and policies.

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

Table 6, continued. Geologic resource laws, regulations, and policies.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Nonfederal minerals other than oil and gas	**NPS Organic Act, 54 USC §§ 100101 and 100751**	**NPS regulations at 36 CFR Parts 1, 5, and 6** require the owners/operators of other types of mineral rights to obtain a special use permit from the NPS as a **§ 5.3** business operation, and **§ 5.7** – Construction of buildings or other facilities, and to comply with the solid waste regulations at **Part 6**.	**Section 8.7.3** states that operators exercising rights in a park unit must comply with **36 CFR Parts 1** and **5**.
Coal	**Surface Mining Control and Reclamation Act of 1977, 30 USC § 1201 et. seq.** prohibits surface coal mining operations on any lands within the boundaries of a NPS unit, subject to valid existing rights.	**SMCRA Regulations at 30 CFR Chapter VII** govern surface mining operations on Federal lands and Indian lands by requiring permits, bonding, insurance, reclamation , and employee protection. **Part 7** of the regulations states that National Park System lands are unsuitable for surface mining.	None Applicable.
Uranium	**Atomic Energy Act of 1954:** Allows Secretary of Energy to issue leases or permits for uranium on BLM lands; may issue leases or permits in NPS areas only if president declares a national emergency.	None Applicable.	None Applicable.
Climate Change	**Secretarial Order 3289** (Addressing the Impacts of Climate Change on America's Water, Land, and Other Natural and Cultural Resources) (2009) requires DOI bureaus and offices to incorporate climate change impacts into long-range planning; and establishes DOI regional climate change response centers and Landscape Conservation Cooperatives to better integrate science and management to address climate change and other landscape scale issues. **Executive Order 13693** (Planning for Federal Sustainability in the Next Decade) (2015) established to maintain Federal leadership in sustainability and greenhouse gas emission reductions.	None Applicable.	**Section 4.1** requires NPS to investigate the possibility to restore natural ecosystem functioning that has been disrupted by past or ongoing human activities. This would include climate change, as put forth by Beavers et al. (in review). **Policy Memo 12-02** (Applying National Park Service Management Policies in the Context of Climate Change) (2012) applies considerations of climate change to the impairment prohibition and to maintaining "natural conditions". **Policy Memo 14-02** (Climate Change and Stewardship of Cultural Resources) (2014) provides guidance and direction regarding the stewardship of cultural resources in relation to climate change. **Policy Memo 15-01** (Climate Change and Natural Hazards for Facilities) (2015) provides guidance on the design of facilities to incorporate impacts of climate change adaptation and natural hazards when making decisions in national parks.

Table 6, continued. Geologic resource laws, regulations, and policies.

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

Table 6, continued. Geologic resource laws, regulations, and policies.

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

Table 6, continued. Geologic resource laws, regulations, and policies.

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

Additional References, Resources, and Websites

California Geology

- California Coastal Records Project (aerial photographs of the California coast): https://www.californiacoastline.org/cgi-bin/imagerandom.cgi. To request permission to use photographs, see contact information at https://www.californiacoastline.org/contact.html.
- California Seafloor Mapping Program: https://www.usgs.gov/centers/pcmsc/science/california-seafloor-mapping-program?qt-science_center_objects=0#qt-science_center_objects
- California Geological Survey (CGS) Notes (short pamphlets that contain answers to commonly asked questions about California's geology): https://www.conservation.ca.gov/cgs/publications/cgs-notes
- Geological Gems of the California State Parks (CGS publication series, also known as Geo Gems): https://www.parks.ca.gov/?page_id=29631

Cascadia Subduction Zone

- Plate Boundary Observatory (PBO) Network (online map): https://www.unavco.org/instrumentation/networks/status/pbo
- PBO Network (education and outreach materials): https://www.unavco.org/education/outreach/outreach.html
- Pacific Northwest Seismic Network (PNSN): https://pnsn.org/outreach
- University of Washington, Natural Hazards, M9 [magnitude 9] Project: https://hazards.uw.edu/geology/m9/
- YouTube—animation of Cascadia earthquakes from September 1979 to August 2019, posted 3 September 2019 by the National Weather Service (compiles USGS data from https://earthquake.usgs.gov/earthquakes/search/): https://www.youtube.com/watch?v=wAJcLtBhNEM

Climate Change

- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/
- NPS Climate Change Response Program: http://www.nps.gov/subjects/climatechange/resources.htm
- NPS sea level rise map viewer: https://maps.nps.gov/slr/
- NPS sea level change: https://www.nps.gov/subjects/climatechange/sealevelchange.htm/index.htm
- Redwood and Climate Change Initiative (a research program led by Save the Redwoods League and Humboldt State University): https://www.savetheredwoods.org/tag/redwood-and-climate-change-initiative/
- US Global Change Research Program: http://www.globalchange.gov/home

Faults and Earthquakes in California

- California Geological Survey (CGS) earthquake and fault information (with links to information about recent earthquakes, historical earthquakes, faults, earthquake probabilities, earthquake shaking hazard, and earthquake loss estimation): https://www.conservation.ca.gov/cgs/earthquakes
- CGS earthquake zones of required investigation: https://maps.conservation.ca.gov/cgs/EQZApp/app/
- California Integrated Seismic Network (CISN; real-time earthquake map of California): https://www.cisn.org/map/index.html
- CGS Map Sheet 48 (earthquake shaking potential for California): https://data.ca.gov/dataset/cgs-map-sheet-48-earthquake-shaking-potential-for-california-revised-20161
- CGS Note 31 (faults and earthquakes in California): https://www.conservation.ca.gov/cgs/publications/cgs-notes
- CISN ShakeMaps (depict the intensity of ground shaking for earthquakes of magnitude 3.5 and greater): https://www.cisn.org/services/shakemap.html
- *Living on Shaky Ground: How to Survive Earthquakes and Tsunami in Northern California* (Dengler et al. 2016) summarizes earthquake-related hazards and provides information about how to prepare for them.
- Quaternary faults offshore of California: https://www.sciencebase.gov/catalog/item/5d38b842e4b01d82ce8b9b56
- ShakeAlert (an earthquake early warning system for the west coast of the United States, sponsored by the USGS): https://www.shakealert.org/
- *Shake, Rattle, and Roll—Awaking the Public's Curiosity of Geology via Interpretation* (Natoli and Lillie 2006) may assist park staff in educating the public about earthquake hazards at the parks. Contact the GRI team for a copy.
- USGS Earthquake Hazards Program unified hazard tool: https://earthquake.usgs.gov/hazards/interactive/
- USGS US Quaternary faults online map viewer: https://usgs.maps.arcgis.com/apps/webappviewer/index.html?id=5a6038b3a1684561a9b0aadf88412fcf
- Working Group on California Earthquake Probabilities: http://www.wgcep.org/

Geologic Maps

- American Geosciences Institute provides information about geologic maps and their uses: http://www.

americangeosciences.org/environment/publications/mapping

- National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/ngmdb/ngmdb_home.html
- Geologic Names Lexicon (Geolex; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/search

Geological Surveys and Societies

- American Geophysical Union: http://sites.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: http://www.stategeologists.org/
- California Geological Survey (CGS): https://www.conservation.ca.gov/cgs/Pages/Index.aspx
- Geological Society of America: http://www.geosociety.org/
- International Union of Geological Sciences (IUGS), International Commission on Stratigraphy (ICS): https://stratigraphy.org/; see https://stratigraphy.org/chart for the international chronostratigraphic chart ("geologic time scale")
- US Geological Survey: http://www.usgs.gov/

Geology of National Park Service Areas

- NPS Geologic Resources Division (GRD): http://go.nps.gov/geology
- GRD geoscience concepts: http://go.nps.gov/geoeducation
- NPS Geologic Resources Inventory: http://go.nps.gov/gri

Landslides

- California Geological Survey (CGS) information about landslides: https://www.conservation.ca.gov/cgs/landslides
- CGS landslide inventory: https://maps.conservation.ca.gov/cgs/lsi/app/
- CGS Note 50 (factors affecting landslides in forested terrain): https://www.conservation.ca.gov/cgs/publications/cgs-notes
- *The Landslide Handbook—A Guide to Understanding Landslides* (Highland and Bobrowsky 2008): http://pubs.usgs.gov/circ/1325/
- Last Chance Grade Project: https://lastchancegrade.com/
- The "Monitoring Slope Movements" chapter (Wieczorek and Snyder 2009) of *Geological Monitoring* (Young and Norby 2009): https://www.nps.gov/articles/monitoring-slope-movements.htm

Offshore and Coastal Geology

- California Seafloor Mapping Program (USGS): https://www.usgs.gov/centers/pcmsc/science/california-seafloor-mapping-program
- California State Waters Map Series Data Catalog: https://pubs.usgs.gov/ds/781/
- COAST NPS SharePoint site: https://doimspp.sharepoint.com/sites/nps-coast (available on NPS computers only). COAST is a Community of Practice (CoP) for people interested in meeting the challenges confronting oceans and coasts. Information about the Benthic Habitat Mapping and other priority projects can be found here.
- Natural Resource Conservation Service (NRCS) subaqueous soil surveys: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/ref/?cid=nrcseprd1343022
- NPS benthic habitat mapping, data availability: https://www.nps.gov/gis/storymaps/mapseries/v2/index.html?appid=90f695c68cc648b7980a151eafd9d9b7
- NPS Submerged Resources Center: https://www.nps.gov/orgs/1635/index.htm. Although the center focuses on cultural resources, it may be able to provide guidance for collecting offshore data because it embraces an interdisciplinary approach to resource management issues and works actively across disciplines to provide science-based recommendations to park managers and partners in line with the preservation mandate of the National Park Service.
- NPS Ocean and Coastal Resources Program (OCRP), part of the Water Resources Division: https://www.nps.gov/orgs/1439/ocrb.htm

Redwoods Rising

- Redwoods Rising (Save the Redwoods League): https://www.savetheredwoods.org/project/redwoods-rising/
- Redwoods Rising (National Park Service): https://www.nps.gov/redw/redwoodsrisingmain.htm

Shoreline Length

- NOAA Continually Updated Shoreline Project: https://coast.noaa.gov/digitalcoast/data/cusp.html. *Note*: Management at the parks uses these data (Dave Best, Redwood National and State Parks, GIS and information management, written communication, 25 March 2021).
- USGS National Hydrography Dataset (NHD): https://www.usgs.gov/core-science-systems/ngp/national-hydrography/national-hydrography-dataset?qt-science_support_page_related_con=0#qt-science_support_page_related_con. *Note*: NHD

data are mapped at a scale of 1:24,000 or larger, except in Alaska where mapping is 1:63,360 scale or larger. Coastlines mapped at 1:24,000 scale are more detailed, potentially resulting in "more length," than those mapped at 1:63,360 scale. As such, a coastline mapped at a scale of 1:24,000 may trace more features and appear longer than the same coastline mapped at a scale of 1:63,360.

- *Shoreline Length and Water Area in the Ocean, Coastal and Great Lakes Parks: Updated Statistics for Shoreline Miles and Water Acres* (Curdts 2011): https://irma.nps.gov/DataStore/Reference/Profile/2180595. *Note*: Curdts (2011) used the NHD for measuring "shoreline miles" in Redwood National and State Parks. The NPS Water Resources Division and Ocean and Coastal Resources Program used Curdts (2011) to obtain a servicewide estimate of shoreline length (18,048 km [11,217 mi]).

Tsunamis

- Alaska earthquake (magnitude 9.2) and tsunami of 27 March 1964: https://earthquake.usgs.gov/earthquakes/events/alaska1964/
- California Geological Survey (CGS) interactive tsunami maps (show tsunami inundation zones, including Humboldt and Del Norte Counties): https://www.conservation.ca.gov/cgs/tsunami/maps
- CGS tsunami informational brochures, posters, and videos: https://www.conservation.ca.gov/cgs/tsunami/education
- NOAA, Deep-Ocean Assessment and Reporting of Tsunamis (DART) stations: https://www.ndbc.noaa.gov/dart/dart.shtml
- Redwood Coast Tsunami Work Group (RCTWG): https://rctwg.humboldt.edu/home
- RCTWG member organizations: https://rctwg.humboldt.edu/member-organizations
- Tsunami warning centers: https://www.weather.gov/safety/tsunami-twc

US Geological Survey Reference Tools

- Geographic Names Information System (GNIS; official listing of place names and geographic features): https://www.usgs.gov/core-science-systems/ngp/board-on-geographic-names
- GeoPDFs (download PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")
- Stream statistics for Redwood Creek at Orick, California: https://streamstatsags.cr.usgs.gov/gagepages/html/11482500.htm
- Tapestry of Time and Terrain (descriptions of physiographic provinces): http://pubs.usgs.gov/imap/i2720/
- USGS Publications Warehouse: http://pubs.er.usgs.gov

Literature Cited

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

Aalto, K. R. 1981. Geologic map of the Crescent City quadrangle, Del Norte County, California (scale 1:62,500). Unpublished mapping for Data Base Augmentation Program. California Division of Mines and Geology, Sacramento, California.

Aalto, K. R. 1989. Geology of Patrick's Point State Park, Humboldt County, northern California. California Geology 42:125–133.

Aalto, K. R. 2006. The Klamath peneplain: a review of J.S. Diller's classic erosion surface. Pages 451–463 *in* A. W. Snoke and C. G. Barnes, editors. Geological studies in the Klamath Mountains province, California and Oregon: a volume in honor of William P. Irwin. Special Paper 410. Geological Society of America, Boulder, Colorado.

Aalto, K. R., P. H. Cashman, S. M. Cashman, and H. M. Kelsey. 1981. Geology of the Coast Ranges, Del Norte and northern Humboldt Counties, California (scales 1:62,500 and 1:24,000). Unpublished data. California Division of Mines and Geology, Data Base Augmentation Program, Sacramento, California.

Aalto, K. R., B. L. Court, and D. C. Engebretson. 1983. Structure, paleontology and paleomagnetism of the mouth-of-the Klamath chert, Franciscan Complex, northern California. Geological Society of America Abstracts with Programs 15(5):314.

Aalto, K. R., and G. D. Harper. 1982. Geology of the Coast Ranges in the Klamath and part of the Ship Mountain 15-minute quadrangles, Del Norte County, California (scale 1:62,500). Open-File Report OFR-82-16. California Division of Mines and Geology, Sacramento, California.

Aalto, K. R., W. D. Sharp, and P. R. Renne. 1998. ^{40}Ar/^{39}Ar dating of detrital micas from Oligocene–Pleistocene sandstones of the Olympic Peninsula, Klamath Mountains and northern California Coast Ranges: provenance and paleodrainage patterns. Canadian Journal of Earth Sciences 35:735–745. doi:10.1139/cjes-35-7-735.

Abramson, H. F. 1998. Evidence for tsunami and earthquakes during the last 3500 years from Lagoon Creek, a coastal freshwater marsh, northern California. Thesis. Humboldt State University, Arcata, California.

Abramson, H. F., C. E. Garrison-Laney, and G. A. Carver. 1998. Evidence for earthquakes and tsunamis during the last 3500 years from Lagoon Creek, a coastal freshwater marsh, northern California. Abstract 11191. Geological Society of America Abstracts with Programs 30(5):2.

Addicott, W. O. 1963. Interpretation of the invertebrate fauna from the upper Pleistocene Battery Formation near Crescent City, California. Proceedings, California Academy of Sciences XXXI:341–347.

Alexander, E. B., R. G. Coleman, T. Keeler-Wolf, and S. Harrison. 2007. Serpentine geoecology of western North America: geology, soils, and vegetation. Oxford University Press, New York, New York.

Ammann, K., and P. Raimondi. 2008. Final long-term monitoring protocol for rocky intertidal communities of Redwood National and State Parks, California. Natural Resource Report NPS/KLMN/NRR—2008/034. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/653353.

Ammann, K. N., P. T. Raimondi, and D. P. Lohse. 2017. Rocky intertidal monitoring: 2015 results from Redwood National and State Parks. Natural Resource Report NPS/KLMN/NRR—2017/1489. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2243053.

Atwater, B. F., S. Musumi-Rokkaku, K. Satake, Y. Tsuji, K. Ueda, and D. K. Yamaguchi. 2015. The orphan tsunami of 1700: Japanese clues to a parent earthquake in North America. Second edition. University of Washington Press, Seattle, Washington. Available online as US Geological Survey Professional Paper 1707. https://pubs.er.usgs.gov/publication/pp1707.

Back, W. 1957. Geology and ground-water features of the Smith River plain, Del Norte County, California (scale 1:62,500). Water Supply Paper 1254. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/wsp1254.

Bailey, E. H., W. P. Irwin, and D. L. Jones. 1964. Franciscan and related rocks and their significance in the geology of western California. California Division of Mines and Geology Bulletin 183:15–20.

Banasiak, A., L. Bilmes, and J. Loomis. 2015. Carbon sequestration in the US national parks: a value beyond visitation. Discussion Paper 2015-66 (February 2015). Harvard Kennedy School, Project on Climate Agreements, Cambridge, Massachusetts. https://www.belfercenter.org/publication/carbon-sequestration-us-national-parks-value-beyond-visitation.

Barberopoulou, A., J. C. Borrero, B. Uslu, M. R. Legg, and C. E. Synolakis. 2011. A second generation of tsunami inundation maps for the State of California. Pure and Applied Geophysics 168(11):2133–2146. https://doi.org/10.1007/s00024-011-0293-3.

Barr, B. R., M. E. Koopman, C. D. Williams, S. Vynne, R. Hamilton, and B. Doppelt. 2010. Preparing for climate change in the Klamath basin. National Center for Conservation Science and Policy, Ashland, Oregon, and Climate Leadership Initiative, San Francisco, California. https://scholarsbank.uoregon.edu/xmlui/handle/1794/10722.

Barrón, E., and C. Diéguez. 2001. Estudio macrofl orístico del Mioceno Inferior lacustre de la Cuenca de Rubielos de Mora (Teruel, España). Boletín Geológico y Minero 112:13–56. [In Spanish.]

Bartholow, J. M. 2005. Recent water temperature trends in the Lower Klamath River, California. North American Journal of Fisheries Management 25(1):152-162.

Bates, B. C., Z. W. Kundzewicz, S. Wu, and J. P. Palutikof, editors. 2008. Climate change and water. Technical Paper of the Intergovernmental Panel on Climate Change (IPCC). IPCC Secretariat, Geneva, Switzerland. https://www.ipcc.ch/publication/climate-change-and-water-2/.

Bauer, S., J. Olson, A. Cockrill, M. van Hattem, L. Miller, M. Tauzer, and G. Leppig. 2015. Impacts of surface water diversions for marijuana cultivation on aquatic habitat in four northwestern California watersheds. PLoS ONE 10(3):e0120016. doi:10.1371/journal.pone.0120016. https://irma.nps.gov/DataStore/DownloadFile/562502.

Beavers, R. L., A. L. Babson, and C. A. Schupp. 2016. Coastal adaptation strategies handbook. NPS 999/134090. National Park Service, Washington, DC. https://www.nps.gov/subjects/climatechange/coastalhandbook.htm.

Bellmore, J. R., G. R. Pess, J. J. Duda, J. E. O'Connor, A. E. East, M. M. Foley, A. C. Wilcox, J. J. Major, P. B. Shafroth, S. A. Morley, C. S. Magirl, C. W. Anderson, J. E. Evans, C. E. Torgersen, and L. S. Craig. 2019. Conceptualizing ecological responses to dam removal: If you remove it, what's to come? BioScience 69(1):26–39. https://doi.org/10.1093/biosci/biy152.

Best, D. W. 1995. History of timber harvest in the Redwood Creek basin, northwestern California. Chapter C *in* K. M. Nolan, H. M. Kelsey, and D. C. Marron, editors. Geomorphic processes and aquatic habitat in the Redwood Creek basin, northwestern California. Professional Paper 1454. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/pp1454.

Blake, M. C., W. P. Irwin, and R. G. Coleman. 1967. Upside-down metamorphic zonation, blueschist facies, along a regional thrust in California and Oregon. Pages C1–C9 *in* Scientific notes and summaries of investigations in geology, hydrology, and related fields. Geological survey research 1967, chapter C. Professional Paper 575-C. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/pp575C.

Borgeld, J. C. 1985. Holocene stratigraphy and sedimentation on the northern California continental shelf. Dissertation. University of Washington, Seattle, Washington.

Borgeld, J. C., G. Crawford, S. F. Craig, E. D. Morris, B. David, D. G. Anderson, C. McGary, and V. Ozaki. 2007. Assessment of coastal and marine resources and watershed conditions at Redwood National and State Parks, California. Natural Resource Technical Report NPS/NRWRD/NRTR—2007/368. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/650161.

Boyd, M. J., and J. D. DeMartini. 1977. Intertidal and subtidal biota of Redwood National Park. US Department of the Interior, National Park Service contract number CX8480-4-0665. Humboldt State University, Arcata, California. http://humboldt-dspace.calstate.edu/handle/2148/445.

Boyd, M., J. D. DeMartini, and G. Pic'l. 1981. Reconnaissance survey of Redwood National Park Area of Special Biological Significance. A report to the California Department of Fish and Game and the California State Water Resources Control Board. Humboldt State University, Arcata, California. https://irma.nps.gov/DataStore/Reference/Profile/101936.

Brabb, E. E., and E. H. Pampeyan. 1972. Preliminary geologic map of San Mateo County, California (scale 1:62,500). Miscellaneous Field Studies Map MF-328. US Geological Survey, Reston, Virginia. https://ngmdb.usgs.gov/Prodesc/proddesc_48.htm.

Bradley, W. C., and G. B. Griggs. 1976. Form, genesis, and deformation of central California wave-cut platforms. Geological Society of America Bulletin 87:433–449.

Bureau of Land Management. 2019. California Coastal National Monument. Online information. US Department of the Interior, Bureau of Land Management, California State Office, Sacramento, California. https://www.blm.gov/programs/national-conservation-lands/california/california-coastal (accessed 20 August 2019).

Burns, E., and S. Sillett. 2019. Discovering the climate change resilience of coast redwood forests. Redwoods (the magazine of Save the Redwoods League) Spring/Summer 2019:35–43. https://www.savetheredwoods.org/redwoods-magazine/spring-2019/discovering-the-climate-change-resilience-of-coast-redwood-forests/.

Bush, D. M., and R. Young. 2009. Coastal features and processes. Pages 47–67 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. https://www.nps.gov/subjects/geology/geological-monitoring.htm.

Busing, R. T., and T. Fujimori. 2005. Biomass, production and woody detritus in an old coast redwood (*Sequoia sempervirens*) forest. Plant Ecology 177:177–188.

Caffrey, M. A., R. L. Beavers, and C. H. Hoffman. 2018. Sea level rise and storm surge projections for the National Park Service. Natural Resource Report NPS/NRSS/NRR—2018/1648. National Park Service, Fort Collins, Colorado. https://www.nps.gov/subjects/climatechange/sealevelchange.htm/index.htm.

California Department of Forestry and Fire Protection. 2021. Forest practice. Online information. State of California, Department of Forestry and Fire Protection, Sacramento, California. https://www.fire.ca.gov/programs/resource-management/forest-practice/ (accessed 5 January 2021).

California Department of Transportation. 2016. Last Chance Grade project study report. California Department of Transportation, District 1, Eureka, California. https://lastchancegrade.com/app_pages/view/50.

California Department of Transportation. 2017. Last Chance Grade: project timeline. California Department of Transportation, District 1, Eureka, California. https://lastchancegrade.com/app_pages/view/13.

California Department of Transportation. 2019. Last Chance Grade. Online information. California Department of Transportation, District 1, Eureka, California. https://lastchancegrade.com/ (accessed 25 November 2019).

California Environmental Protection Agency. 2019. Impaired water bodies. Final 2014/2016 California integrated report (Clean Water Act Section 303(d) List / 305(b) Report). California Environmental Protection Agency, State Water Resources Control Board, Sacramento, California. https://www.waterboards.ca.gov/water_issues/programs/tmdl/integrated2014_2016.shtml.

California Geological Survey. 2013. Factors affecting landslides in forested terrain. Note 50. California Department of Conservation, California Geological Survey, Sacramento, California. https://www.conservation.ca.gov/cgs/publications/cgs-notes.

Carver, D. H. 1998. Native stories of earthquakes and tsunamis, Redwood National Park, California. Contract 1443PX848098092. National Park Service, Crescent City, California. https://irma.nps.gov/DataStore/Reference/Profile/599488.

Carver, D. H., and G. A. Carver. 1996. Earthquake and thunder—native oral histories of paleoseismicity along the southern Cascadia subduction zone. Abstract 3039. Geological Society of America Abstracts with Programs 28(5):54.

Carver, G. A. 1992. Late Cenozoic tectonics of coastal northern California. Pages 1–10 *in* G. A. Carver and K. R. Aalto, editors. Field guide to the late Cenozoic subduction tectonics and sedimentation of northern coastal California. Field Guide GB-71. American Association of Petroleum Geologists, Pacific Section, Bakersfield, California.

Cashman, S. M., H. M. Kelsey, and D. R. Harden. 1995. Geology of the Redwood Creek basin, Humboldt County, California. Chapter B *in* K. M. Nolan, M. Kelsey, and D. C. Marron, editors. Geomorphic processes and aquatic habitat in the Redwood Creek basin, northwestern California. Professional Paper 1454. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/pp1454.

Caughman, M., and J. S. Ginsberg. 1987. California coastal resource guide. California Coastal Commission, Berkeley, California.

Cervantes, J. 2006. Marijuana horticulture: the indoor/outdoor medical grower's bible. Van Patten Publishers, Sacramento, California.

Chaney, R. W. 1948a. Redwoods around the Pacific basin. Pacific Discovery 1(5):4–14.

Chaney, R. W. 1948b. Redwoods in China. Natural History 57(10):440–444.

Chaney, R. W. 1951. A revision of fossil *Sequoia* and *Taxodium* in western North America based on the recent discovery of *Metasequoia*. Transactions of the American Philosophical Society, New Series 40:171–263.

Chen, F., X. Y. Meng, S. Q. Ren, and C. L. Wu. 1988. The Early Cretaceous flora of Fuxin basin and Tiefa basin, Liaoning Province. Geological Publishing House, Beijing, Beijing, China. [In Chinese.]

Clague, J., and B. Turner. 2003. Vancouver, city on the edge: living with a dynamic geological landscape. Tricouni Press, Vancouver, British Columbia, Canada.

Clarke, S. H. Jr. 1992. Geology of the Eel River basin and adjacent region: implications for late Cenozoic tectonics of the southern Cascadia subduction zone and Mendocino triple junction. AAPG [American Association of Petroleum Geologists] Bulletin 76(2):199–224.

Clarke, S. H. Jr., and G. A. Carver. 1992. Late Holocene tectonics and paleoseismicity, southern Cascadia subduction zone. Science 255(5041):188–192.

Clarke Historical Museum. 2018. Gold rush. Online information. Clarke Historical Museum, Eureka, California. http://www.clarkemuseum.org/gold-rush.html (accessed 20 August 2019).

Connell, S. C., J. W. Hawley, and D. W. Love. 2005. Late Cenozoic drainage and development in the southeastern Basin and Range of New Mexico, southeasternmost Arizona, and western Texas. Pages 125–150 *in* S. G. Lucas, G. S. Logan, and K. E. Zeigler, editors. New Mexico's ice ages. Bulletin 28. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico.

Covington, S. 2004. Redwood National and State Parks, geologic resources management issues, scoping summary (27 August 2004). National Park Service, Geologic Resources Division, Lakewood, Colorado. https://www.nps.gov/subjects/geology/geologic-resources-inventory-products.htm.

Cowan, D. S. 1985. Structural styles in Mesozoic and Cenozoic mélanges in the western Cordillera of North America. Geological Society of America Bulletin 96:451–462.

Criswell, R. 1968. A paleontological study of the Gold Bluffs area of Prairie Creek Redwoods State Park, California. Unpublished study. Humboldt State College, Arcata, California.

Cronin, V. S. 2021. Triple junctions. Entry *in* D. Alderton and S. A. Elias, editors. Encyclopedia of geology, second edition. Academic Press, Elsevier, Amsterdam, The Netherlands. https://doi.org/10.1016/B978-0-12-409548-9.12130-X.

Crouch, J. K., and J. Suppe. 1993. Late Cenozoic tectonic evolution of the Los Angeles basin and California borderland: a model for core complex-like crustal extension. Geological Society of America Bulletin 105:1415–1434.

Cruden, D. M., and Varnes, D. L. 1996. Landslide types and processes. Pages 36–75 (chapter 3) *in* A. K. Turner and R. L. Schuster, editors. Landslides: investigation and mitigation. Special Report 247. Transportation Research Board, National Research Council, Washington, DC.

Curdts, T. 2011. Shoreline length and water area in the ocean, coastal and Great Lakes parks: updated statistics for shoreline miles and water acres (rev1b). Natural Resource Report NPS/WASO/NRR—2011/464. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2180595.

Davenport, C. W. 1982. Geology and geomorphic features related to landsliding, Crescent City 7.5' quadrangle, Del Norte County, California (scale 1:24,000). Open-File Report 82-21 SF. California Division of Mines and Geology, Sacramento, California.

Davenport, C. W. 1983a. Geology and geomorphic features related to landsliding, High Divide 7.5' quadrangle, Del Norte County, California (scale 1:24,000). Open-File Report 83-18 SF. California Division of Mines and Geology, Sacramento, California.

Davenport, C. W. 1983b. Geology and geomorphic features related to landsliding, Hiouchi 7.5' quadrangle, Del Norte County, California (scale 1:24,000). Open-File Report 83-04 SF. California Division of Mines and Geology, Sacramento, California.

Davenport, C. W. 1983c. Geology and geomorphic features related to landsliding, Smith River 7.5' quadrangle, Del Norte County, California (scale 1:24,000). Open-File Report 83-19 SF. California Division of Mines and Geology, Sacramento, California.

Davenport, C. W. 1984a. Geology and geomorphic features related to landsliding, Childs Hill 7.5’ quadrangle, Del Norte County, California (scale 1:24,000). Open-File Report OFR 84-7 SF. California Division of Mines and Geology, Sacramento, California.

Davenport, C. W. 1984b. Geology and geomorphic features related to landsliding, Requa 7.5’ quadrangle, Del Norte County, California (scale 1:24,000). Open-File Report OFR 84-8 SF. California Division of Mines and Geology, Sacramento, California.

Davey, C. A., K. T. Redmond, and D. B. Simeral. 2007. Weather and climate inventory, National Park Service, Klamath Network. Natural Resource Technical Report NPS/KLMN/NRTR—2007/035. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/649238.

Delattre, M., and A. Rosinski. 2012. Preliminary geologic map of the onshore portions of the Crescent City and Orick 30' × 60' quadrangles, California (scale 1:100,000). California Geological Survey, Sacramento, California. https://www.conservation.ca.gov/cgs/maps-data/rgm/preliminary#30x60quads.

Dell’Osso, D. R., J. N. Falls, and D. J. McGuire. 2002a. Geologic and geomorphic features related to landsliding, Redwood Creek watershed, Humboldt County, California (scale 1:24,000). Plate 1 (includes 3 sheets—north, central, and south) in Watershed Mapping Series, Map Set 6. California Geological Survey, Sacramento, California. https://www.conservation.ca.gov/cgs/Pages/Program-FWGP/redwood.aspx.

Dell’Osso, D. R., J. N. Falls, and D. J. McGuire. 2002b. Relative landslide potential with geologic and geomorphic features, Redwood Creek watershed, Humboldt County, California (scale 1:24,000). Plate 2 (includes 3 sheets—north, central, and south) in Watershed Mapping Series, Map Set 6. California Geological Survey, Sacramento, California. https://www.conservation.ca.gov/cgs/Pages/Program-FWGP/redwood.aspx.

Dell’Osso, D. R., J. N. Falls, and D. J. McGuire. 2003. Maps, GIS data and geologic report for the Watershed Mapping Series, Map Set 6: Redwood Creek watershed, Humboldt County, California. CD 2002-10. California Geological Survey, Sacramento, California.

Dengler, L., M. Hemphill-Haley, V. Felton, A. Monro, and J. Warren. 2016. Living on shaky ground: how to survive earthquakes and tsunami in northern California. Humboldt State University, Humboldt Earthquake Education Center, Arcata, California. https://www2.humboldt.edu/shakyground/.

Diller, J. S. 1902. Topographic development of the Klamath Mountains. Bulletin 196. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b196.

Doppelt, B., R. Hamilton, C. Williams, and M. Koopman. 2008. Preparing for climate change in the Rogue River basin of southwest Oregon. University of Oregon, Institute for Sustainable Environment, Eugene, Oregon.

Dott, R. H. Jr. 1965. Mesozoic–Cenozoic tectonic history of the southwestern Oregon coast in relation to cordilleran orogenesis. Journal of Geophysical Research 70(18):4687–4707.

Duda, J. J., J. H. Anderson, M. M. Beirne, S. Brenkman, P. Crain, J. Mahan, M. McHenry, G. Pess, R. Peters, and B. Winter. 2019. Complexities, context, and new information about the Elwha River. Frontiers in Ecology and the Environment 17(1):10–11. https://doi.org/10.1002/fee.1989.

Earle, C. J., editor. 2019. The gymnosperm database: *Sequoia sempervirens* (D. Don) Endlicher 1847. Online information. https://www.conifers.org/cu/Sequoia.php (accessed 10 May 2021).

East, A. E., J. B. Logan, M. C. Mastin, A. C. Ritchie, J. A. Bountry, C. S. Magirl, and J. B. Sankey. 2018. Geomorphic evolution of a gravel-bed river under sediment-starved versus sediment-rich conditions: river response to the world’s largest dam removal. Journal of Geophysical Research: Earth Surface 123:3338–3369. https://doi.org/10.1029/2018JF004703.

East, A. E., G. R. Pess, J. A. Bountry, C. S. Magirl, A. C. Ritchie, J. B. Logan, T. J. Randle, M. C. Mastin, J. T. Minear, J. J. Duda, M. C. Liermann, M. L. McHenry, T. J. Beechie, and P. B. Shafroth. 2015. Large-scale dam removal on the Elwha River, Washington, USA: river channel and floodplain geomorphic change. Geomorphology 228:765–786.

Elder, D., and M. Reichert. 2010. Region-wide GIS bedrock compilation mapping—an ArcSDE geodatabase, version 2.0: digital dataset. Internal publication. USDA Forest Service, Pacific Southwest Region, Vallejo, California.

Endo, S. 1951. A record of *Sequoia* from the Jurassic of Manchuria. Botanical Gazette 113:228–230.

Erd, R. C., and G. K. Czamanske. 1983. Orickite and coyoteite, two new sulfide minerals from Coyote Peak, Humboldt County, California. American Mineralogist 68(1–2): 245–254.

Ernst, W. G. 1983. Phanerozoic continental accretion and the metamorphic evolution of northern and central California. Tectonophysics 100(1–3):287–320.

Evans, J. G. 1984. Structure of part of the Josephine peridotite, northern California and southwestern Oregon [including plate 1: Reconnaissance geologic map of the Josephine Peridotite and associated rocks, northwestern California and southwestern Oregon (scale 1:125,000)]. Bulletin 1546-A. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/b1546AD.

Evans, H. T., and J. R. Clark. 1981. The crystal structure of bartonite, a potassium iron sulfide, and its relationship to pentlandite and djerfisherite American Mineralogist 66:376–384.

Falls, N. J., D. J. McGuire, and D. R. Dell'Osso. 2003. Report on the geologic and fluvial geomorphic characteristics of the Redwood Creek watershed, California. Report to accompany D. R. Dell'Osso, J. N. Falls, and D. J. McGuire (2002), plates 1 and 2 of Watershed Mapping Series, Map Set 6. California Geological Survey, Sacramento, California. https://www.conservation.ca.gov/cgs/Pages/Program-FWGP/redwood.aspx.

Federal Geographic Data Committee, Marine and Coastal Spatial Data Subcommittee. 2012. Coastal and marine ecological classification standard. FGDC-STD-018-2012. National Oceanic and Atmospheric Administration (NOAA) Office for Coastal Management, NOAA Office of Habitat Conservation, US Environmental Protection Agency, US Geological Survey, and NatureServe, Washington, DC. https://iocm.noaa.gov/standards/cmecs-home.html.

Festa, A., B. A. Pini, Y. Dilek, and G. Codegone. 2010. Mélanges and mélange-forming processes: a historical overview and new concepts. International Geology Review 52(10–12):1040–1105.

Field, M. E., S. H. Clarke Jr., and M. E. White. 1980. Geology and geological hazards of offshore Eel River basin, northern California continental margin. Open File Report OFR-80-1080. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/ofr801080.

Foley, M. M., F. J. Magilligan, C. E. Torgersen, J. J. Major, C. W. Anderson, P. J. Connolly, D. Wieferich, P. B. Shafroth, J. E. Evans, D. Infante, L. S. Craig. 2017. Landscape context and the biophysical response of rivers to dam removal in the United States. PLoS ONE 12(7):e0180107. https://doi.org/10.1371/journal.pone.0180107.

Fritsche, A. E., and P. W. Weigand. 2008. Geologic history of the Santa Monica Mountains. Handout provided during the GRI scoping meeting, Santa Monica Mountains National Recreation Area, Thousand Oaks, California, 7 May 2008. California State University, Northridge, Department of Geological Sciences, Northridge, California.

Fuller, M. 2015. Geomorphology and plate tectonics. GeoGem Note 2. Edited by M. Fuller, S. Brown, C. Wills, and W. Short. Geological gems of California state parks. Special Report 230. Interagency Agreement C01718011. California Geological Survey and California State Parks, Sacramento, California. https://www.parks.ca.gov/?page_id=29631.

Fuller, M., S. Brown, C. Wills, and W. Short. 2015. Coast Ranges geomorphic province. GeoGem Note 3. Edited by M. Fuller, S. Brown, C. Wills, and W. Short, editors. Geological gems of California state parks. Special Report 230. Interagency Agreement C01718011. California Geological Survey and California State Parks, Sacramento, California. https://www.parks.ca.gov/?page_id=29631.

Garrison-Laney, C. E. 1998. Diatom evidence for tsunami inundation from Lagoon Creek, a coastal freshwater pond, Del Norte County, California. Thesis. Humboldt State University, Arcata, California.

George, J., and G. M. MacDonald. 2017. Assessing impacts of climate change on species range shifts and extirpation on the local scale through Late Pleistocene fossils of *Sequoia sempervirens* in the Los Angeles Basin. American Geophysical Union, Fall Meeting 2017, abstract #GC33C-1093. https://ui.adsabs.harvard.edu/abs/2017AGUFMGC33C1093G/abstract.

Golden, N. E., compiler. 2019. California State Waters Map Series Data Catalog. Data Series 781. US Geological Survey, Reston, Virginia. https://doi.org/10.3133/ds781.

Golovneva, L. B., and N. B. Nosova. 2012. Albian-Cenomanian flora of western Siberia. Marathon Publishers, St. Petersburg, Russia. [In Russian with English introduction].

Gonzalez, P. 2017. Climate change trends, impacts, and vulnerabilities in US national parks. Pages 102–140 *in* S. R. Beissinger, D. D. Ackerly, H. Doremus, and G. E. Machlis, editors. Science, conservation, and national parks. University of Chicago Press, Chicago, Illinois.

Graham, J. P. 2014. John Day Fossil Beds National Monument: Geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2014/846. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

Graymer, R. W., W. A. Bryant, C. A. McCabe, S. Hecker, and C. S. Prentice. 2006. Map of Quaternary-active faults in the San Francisco Bay region. Scientific Investigations Map SIM-2919. US Geological Survey, Reston, Virginia. http://pubs.usgs.gov/sim/2006/2919.

Grímsson, F., T. Denk, and L. A. Símonarson. 2007. Middle Miocene floras of Iceland—the early colonization of an island? Review of Palaeobotany and Palynology 144:181–219.

Hagans, D. K., and W. E. Weaver. 1987. Magnitude, cause and basin response to fluvial erosion, Redwood Creek basin, northern California. Pages 419–428 *in* R. L. Beschta, T. Blinn, G. E. Grant, E. J. Swanson, and G. G. Ice, editors. Erosion and sedimentation in the Pacific Rim. International Association of Hydrological Sciences (IAHS) publication number 165. IAHS Press, Institute of Hydrology, Wallingford, Oxfordshire, United Kingdom.

Hapke, C. J., D. Reid, B. M. Richmond, P. Ruggiero, and J. List. 2006. National assessment of shoreline change. Part 3: historical shoreline change and associated coastal land loss along sandy shorelines of the California coast. Open File Report 2006-1219. US Geological Survey, Reston, Virginia. https://pubs.usgs.gov/of/2006/1219/.

Harden, D. R. 1998. California geology. Prentice-Hall, Inc. Upper Saddle River, New Jersey.

Harden, D. R., H. M. Kelsey, S. D. Morrison, and T. A. Stephens. 1982. Geologic map of the Redwood Creek drainage basin, Humboldt County, California (scale 1:62,500). Open-File Report OFR-81-496. US Geological Survey, Reston, Virginia. https://doi.org/10.3133/ofr81496 (Note: No digital version available as of 29 October 2019).

Hare, V. C. 2003. Evaluation of a geographic information system model of shallow landsliding in Redwood Creek, California. Thesis. Humboldt State University, Arcata, California. http://humboldt-dspace.calstate.edu/handle/2148/780.

Harper, G. D. 1980. Structure and petrology of the Josephine ophiolite and overlying metasedimentary rocks, northwestern California (scale 1:48,000). Dissertation. University of California, Berkeley, California.

Harper, G. D., J. B. Saleeby, and M. Heizler. 1994. Formation and emplacement of the Josephine ophiolite and the Nevadan orogeny in the Klamath Mountains, California–Oregon: U/Pb zircon and $^{40}Ar/^{39}Ar$ geochronology. Journal of Geophysical Research: Solid Earth 99(B3):4293–4321.

Hazzard, J. C. 1954. Rocks and structure of the northern Providence Mountains, San Bernardino County, California. Pages 27–35 (chapter IV, section 4) *in* R. H. Jahns, editor. Geology of southern California. Bulletin 170. California Division of Mines, Sacramento, California. https://archive.org/details/boxsouthgeology00calirich.

Highland, L. M., and P. Bobrowsky. 2008. The landslide handbook—a guide to understanding landslides. Circular 1325. US Geological Survey, Reston, Virginia. http://pubs.usgs.gov/circ/1325/.

Hofstra, T. D. 1983. Management alternatives for the Redwood Creek estuary, Redwood National Park. Redwood National Park, Crescent City, California. https://irma.nps.gov/DataStore/Reference/Profile/74625.

Hollick, A., and P. S. Smith. 1936. The Tertiary floras of Alaska, with a chapter on the geology of the Tertiary deposits. Professional Paper 182. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/pp182.

Huey, A. S. 1948. Geology of the Tesla quadrangle, California. California Division of Mines Bulletin 140:15–23.

Hults, C. P., and J. Fierstein. 2016. Katmai National Park and Preserve and Alagnak Wild River: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2016/1314. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

Humboldt State University. 2019. What every Northern Californian should know about tsunamis. Online information associated with Living on shaky ground: how to survive earthquakes and tsunami in northern California. Humboldt State University, Humboldt Earthquake Education Center, Arcata, California. http://www2.humboldt.edu/shakyground/info/why_care/northern_california_coast/ (accessed 31 December 2019).

Intergovernmental Panel on Climate Change. 2007. The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Avery, M. Tignor, and H. L. Miller. Cambridge University Press, Cambridge, United Kingdom, and New York, New York.

International Commission on Stratigraphy. 2020. International chronostratigraphic chart (v2020/03). Drafted by K. M. Cohen, D. A. T. Harper, P. L. Gibbard, and J.-X. Fan (March 2020). International Union of Geological Sciences (IUGS), International Commission on Stratigraphy, Durham, England [location of ICS Executive Committee chair as of 11 May 2021]. https://stratigraphy.org/chart.

Irwin. W. P. 1964. Late Mesozoic orogenies in the ultramafic belts of northwestern California and southwestern Oregon. Pages 1–9 *in* Geological Survey Research 1964, Chapter C: scientific notes and summaries of investigations prepared by members of the Geologic and Water Resources Divisions in the fields of geology, hydrology, and related sciences. Professional Paper 501-C. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/pp501C.

Isaak, D., S. Wollrab, D. Horan, and G. Chandler. 2012. Climate change effects on stream and river temperatures across the northwest US from 1980–2009 and implications for salmonid fishes. Climatic Change 113:499–524.

Janda, R. J., K. M. Nolan, D. R. Harden, and S. M. Colman. 1975. Watershed conditions in the drainage basin of Redwood Creek, Humboldt County, California. Open-File Report OFR-75-568. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/ofr75568.

Keller, E. A., and T. Tally. 1979. Effects of large organic debris on channel form and fluvial processes in the coastal redwood environment. Pages 169–197 *in* D. D. Rhodes, and G. P. Williams, editors. Proceedings of the 10th Annual Geomorphology Symposium, State University of New York (SUNY), Binghamton, New York. Kendall/Hunt Publishing Company, Dubuque, Iowa.

KellerLynn, K. 2006. Florissant Fossil Beds National Monument geologic resource evaluation report. Natural Resource Report NPS/NRPC/GRD/NRR—2006/009. National Park Service, Denver, Colorado. http://go.nps.gov/gripubs.

KellerLynn, K. 2015. Bandelier National Monument geologic resources inventory report. Natural Resource Report NPS/NRPC/GRD/NRR—2015/1036. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

KellerLynn, K. 2016. Santa Monica Mountains National Recreation Area geologic resources inventory report. Natural Resource Report NPS/NRPC/GRD/NRR—2016/1297. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

KellerLynn, K. 2018. Cabrillo National Monument geologic resources inventory report. Natural Resource Report NPS/NRPC/GRD/NRR—2018/1666. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

KellerLynn, K. 2020. Tonto National Monument: geologic resources inventory report. Natural Resource Report NPS/NRPC/GRD/NRR—2020/2212. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

Kelsey, H. M., and S. M. Cashman. 1983. Wrench faulting in northern California and its tectonic implications. Tectonics 2(6):565–576.

Kelsey, H. M., M. A. Madej, J. Pitlick, P. Stroud, and M. Coghlan. 1981. Major sediment sources and limits to the effectiveness of erosion control techniques in the highly erosive watersheds of north coastal California. Pages 493–509 *in* T. R. H. Davies and A. J. Pearce, editors. Erosion and sediment transport in Pacific Rim steeplands. International Association of Hydrological Sciences (IAHS) publication number 132. IAHS Press, Institute of Hydrology, Wallingford, Oxfordshire, United Kingdom.

Kelsey, H. M., and J. H. Trexler Jr. 1989. Pleistocene deformation of a portion of the southern Cascadia forearc: Prairie Creek Formation, northern California. Journal of Geophysical Research: Solid Earth 94(B10):14,027–14,039.

Kennedy, G. L., K. R. Lajoie, and J. F. Wehmiller. 1982. Aminostratigraphy and faunal correlations of late Quaternary marine terraces, Pacific Coast, USA. Nature 299:545–547.

Kilbourne, R. T. 1985. Geology and geomorphology related to landsliding, Blue Lake 7.5 minute quadrangle, Humboldt County, California (scale 1:24,000). Open-File Report OFR-85-6. California Division of Mines and Geology, Sacramento, California.

Kilbourne, R. T., and L. Maulchin. 1981. Geology for planning, Crescent City and Sister Rocks 7.5′ quadrangles, Del Norte County, California (scale 1:24,000). Open-File Report OFR-81-01. California Division of Mines and Geology, Sacramento, California.

Kilpper, K. 1968. Koniferen aus den tertiären Deckschichten des Niederrheinischen Hauptflözes, 3. Taxodiaceae und Cupressaceae. Palaeontographica Abt B 124:102–111. [In German.]

Kiparsky, M., and P. H. Gleick. 2003. Climate change and California water resources: a survey and summary of the literature. Report 500-04-073. Pacific Institute for Studies in Development, Environment, and Security, Oakland, California, and California Energy Commission, Sacramento, California.

Kirkham, V. R. D., and M. M. Johnson. 1929. The Latah Formation in Idaho. Journal of Geology 37:483–504.

Klamath River Renewal Corporation (KRRC). 2018. Definite plan for the Lower Klamath Project. Prepared for KRRC by AECOM Technical Services, Inc. (KRRC technical representative), Oakland, California; CDM Smith, Sacramento, California; and River Design Group, Corvallis, Oregon. http://www.klamathrenewal.org/definite-plan/.

Klamath River Renewal Corporation. 2019. FAQs. Online information. Klamath River Renewal Corporation, Berkeley, California. http://www.klamathrenewal.org/faqs/ (accessed 11 May 2021).

Knobloch, E. 1964. Haben Cinnamomum scheuchzeri Heer und Cinnamomum polymorphum (A. Braun) Heer nomenklatorisch richtige Namen? Neues Jahrbuch für Geologie und Paläontologie 10:597–603. [In German.]

Knowles, N., M. D. Dettinger, and D. R. Cayan. 2006. Trends in snowfall versus rainfall in the western United States. Journal of Climate 19(18):4545–4559.

Knowlton, F. H. 1899. Fossil flora of the Yellowstone National Park. Pages 651–882 (chapter XIV) *in* A. Hague, J. P. Iddings, W. H. Weed, C. D. Walcott, G. H. Girty, T. W. Stanton, and F. H. Knowlton, contributors. Geology of the Yellowstone National Park, Part II: descriptive geology, petrography, and paleontology. Monograph XXXII. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/m32.

Knowlton, F. H. 1916. A review of the fossil plants in the United States National Museum from the Florissant Lake Beds at Florissant, Colorado, with a description of new species and a list of type-specimens. Proceedings of the United States National Museum 51(2151):241–297.

Kuebbing, S. E., A. P. Reimer, S. A. Rosenthal, G. Feinberg, A. Leiserowitz, J. A. Lau, M. A. Bradford. 2018. Long term research in ecology and evolution: a survey of challenges and opportunities. Ecological Monography 88(2):245–258. https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1002/ecm.1289.

Lanik, A., D. K. Swanson, and R. D. Karpilo Jr. 2019. Bering Land Bridge National Preserve: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2019/2024. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

Larson, J. P. 1987. Utilization of the Redwood Creek estuary, Humboldt County, California, by juvenile salmonids. Thesis. Humboldt State University, Arcata, California. https://irma.nps.gov/DataStore/Reference/Profile/131825.

Lawson, A. C. 1895. Sketch of the geology of the San Francisco Peninsula. Pages 405–476 *in* J. W. Powell, editor. Fifteenth Annual Report of the United States Geological Survey to the Secretary of the Interior, 1893–1894. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/ar15.

Lesquereux, L. 1876. On the Tertiary flora of the North American lignitic, considered as evidence of the age of the formation. Pages 277–365 *in* F. V. Hayden, editor. [Eighth] Annual Report of the United States Geological and Geographical Survey of the Territories, embracing Colorado and parts of adjacent territories: being a report of progress of the exploration for the year 1874. United States Geological and Geographical Survey of the Territories, Washington, DC. https://www.biodiversitylibrary.org/item/123386#page/587/mode/1up.

Lillie, R. J. 2005. Parks and plates: the geology of our national parks, monuments, and seashores. W. W. Norton and Company, New York, New York, and London, England.

Lohan, T. 2019. Drones, algae and fish ears: what we're learning before the world's largest dam-removal project—and what we could miss. Scientists studying conditions on the Klamath River hope to help recovery efforts here and around the world, but they still lack dedicated funding. Online article published by The Revelator. Center for Biological Diversity, Tucson, Arizona. https://therevelator.org/klamath-dam-science/ (accessed 11 May 2021).

Ma, Q. W., F. L. Li, and C. S. Li. 2005. The coast redwoods (*Sequoia*, Taxodiaceae) from the Eocene Heilongjiang and the Miocene of Yunnan, China. Review of Palaeobotany and Palynology 135:117–129.

MacGinitie, H. D. 1953. Fossil plants of the Florissant beds, Colorado. Carnegie Institution of Washington Publication 599:86–87.

Madej, M. A. 2009. What do landslides have to do with carbon sequestration. Redwood Currents: Resource Management and Science Newsletter 30:20–21. https://irma.nps.gov/DataStore/Reference/Profile/2236441.

Madej, M. A. 2021. Redwood Creek watershed studies: Summary of geomorphic research at Redwood National Park. Natural Resource Report NPS/REDW/NRR—2021/2228. National Park Service, Fort Collins, Colorado. https://doi.org/10.36967/nrr-2284606.

Madej, M., J. Seney, and P. Van Mantgem. 2013. Effects of road decommissioning on carbon stocks and emissions in north coastal California. Restoration Ecology 21:439–446.

Mai, D. H., and H. Walther. 1978. Die floren der Haselbacher Serie im Weisselster-Becken (Bezirk Leipzig, DDR). Abhandlungen des Staatlichen Museums für Mineralogie und Geologie zu Dresden 28:1–200. [In German.]

Major, J. J, J. E. O'Connor, C. J. Podolak, M. K. Keith, G. E. Grant, K. R. Spicer, S. Pittman, H. M. Bragg, J. R. Wallick, D. Q. Tanner, A. Rhode, and P. R. Wilcock. 2012. Geomorphic response of the Sandy River, Oregon, to removal of Marmot Dam. Professional Paper 1792. US Geological Survey, Reston, Virginia. https://pubs.usgs.gov/pp/1792/.

Marvin, R. F., and S. W. Dobson. 1979. US Geological Survey radiometric ages, Compilation "B." Isochron/West 26:3–32.

Maxson, J. H. 1933. Economic geology of portions of Del Norte and Siskiyou Counties, northwesternmost California. California Journal of Mines and Geology 29(1–2):123–160.

McCrory. P. A. 1989. Late Neogene geohistory analysis of the Humboldt basin and its relationship to the convergence of the Juan de Fuca plate. Journal of Geophysical Research 94:3126–3138.

McCulloch, D. S. 1985. Evaluating tsunami potential. Pages 375–413 *in* J. I. Ziony, editor. Evaluating earthquake hazards in the Los Angeles region—an earth science perspective. Professional Paper 1360. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/pp1360.

Melnick, R. Z., V. Malinay, N. P. Kerr, and A. Lewis. 2016. Study of climate change impacts on cultural landscapes in the Pacific West Region, National Park Service. Cultural Landscape Guidance Documents. Cultural Landscape Research Group, University of Oregon, Eugene, Oregon. https://irma.nps.gov/DataStore/Reference/Profile/2238825.

Meyer, H. W. 2003. The fossils of Florissant. Smithsonian Books, Washington, DC, and London, England.

Meyer, H. W., and S. R. Manchester. 1997. The Oligocene Bridge Creek flora of the John Day Formation, Oregon. University of California Publications in Geological Sciences 14:1–195.

Meyers, E. P. III. 1994. Numerical modeling of tsunamis with applications to the Sea of Japan and the Pacific Northwest. Thesis. Oregon Graduate Institute of Science & Technology, Beaverton, Oregon.

Michalak, M. J., T. Esquivel, and O. Helprin. 2016. Project: paleotopography, an ancestral Klamath River, and the provenance of the Prairie Creek Formation. Report for scientific collections permit 16-635-028, Prairie Creek Redwoods State Park. Humboldt State University, Geology Department, Arcata, California.

Milestone, J. 2006. Memorandum re: cyanobacteria to R. B. Howell. National Park Service, Whiskeytown National Recreation Area, Whiskeytown, California. https://irma.nps.gov/DataStore/Reference/Profile/634278 (description only).

Miller, W. III. 1991. Bathysiphonid (Protista: Foraminiferida) localities in Franciscan flysch, northern California, with a redescription of *Bathysiphon aaltoi* Miller, 1986. Tulane Studies in Geology and Paleontology 24:71–78.

Miller, W. III. 1995. Examples of Mesozoic and Cenozoic Bathysiphon (Foraminiferida) from the Pacific Rim and the taxonomic status of *Terebellina Ulrich*, 1904. Journal of Paleontology 69:624–634.

Miller, W. III. 1997. Is *Bathysiphon aaltoi* Miller, 1986 the largest foraminiferid? Tulane Studies in Geology and Paleontology 30(2):117–120. https://journals.tulane.edu/tsgp/article/view/1011.

Monahan, B., and N. Fisichelli. 2014. Recent climate change exposure of Redwood National Park. Climate Change Resource Brief. NPS Inventory & Monitoring Division and Climate Change Response Program, Fort Collins, Colorado. https://irma.nps.gov/Datastore/DownloadFile/497736.

Moore, G. W., and E. A. Silver. 1968. Marine geology: geology of the Klamath River delta, California. Pages C144–C148 *in* Scientific notes and summaries of investigations in geology, hydrology, and related fields. Geological survey research 1968, chapter C. Professional Paper 600-C. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/pp600C.

Morgan, J. W., G.K. Czamanske, and W. A. Gregory. 1985. Origin and evolution of the alkalic ultramafic rocks in the Coyote Peak diatreme, Humboldt County, California. Geochimica et Cosmochimica Acta 49(3):749–759.

Muhs, D. R., T. K. Rockwell, and G. L. Kennedy. 1992. Late Quaternary uplift rates of marine terraces on the Pacific coast of North America, southern Oregon to Baja California sur. Quaternary International 15/16:121–133.

National Marine Fisheries Service. 2014. Final recovery plan for the Southern Oregon/Northern California coast evolutionarily significant unit of coho salmon (*Oncorhynchus kisutch*). National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Washington, DC. https://repository.library.noaa.gov/view/noaa/15985.

National Oceanic and Atmospheric Administration (NOAA). 2021. Tides & currents. Crescent City, CA - Station ID: 9419750. Online information. NOAA, National Ocean Service, Center for Operational Oceanographic Products and Services, Silver Spring, Maryland. https://tidesandcurrents.noaa.gov/stationhome.html?id=9419750 (accessed 10 May 2021).

National Oceanic and Atmospheric Administration, National Park Service, and California State Parks. Publication date unknown. Staying safe on north coast beaches. Brochure [distributed at Redwood National and State Parks, Crescent City, California].

National Park Service. 2010. Manage access to enhance security and protect park resources environmental assessment. National Park Service, Whiskeytown National Recreation Area, Shasta County, California.

National Park Service. 2016a. Foundation document, Redwood National and State Parks. REDW 167/132031. National Park Service, Redwood National and State Parks, Crescent City, California, and Pacific West Region, Oakland, California.

National Park Service. 2016b. Ocean and coastal park jurisdiction handbook. US Department of the Interior, National Park Service, Natural Resource Stewardship and Science, Lakewood, Colorado.

National Park Service. 2019a. Basic information. Online information. Redwood National and State Parks, Crescent City, California. https://www.nps.gov/redw/planyourvisit/basicinfo.htm (accessed 2 July 2019).

National Park Service. 2019b. NPS stats: National Park Service visitor use statistics (sta ts-2.6.1.16577_20190605:03:00:42). Online database. National Park Service, Washington, DC. https://irma.nps.gov/Stats/Reports/Park/REDW (accessed 5 September 2019).

National Park Service. 2020. Elwha River restoration. Online information. Olympic National Park, Port Angeles, Washington. https://www.nps.gov/olym/learn/nature/elwha-ecosystem-restoration.htm (accessed 30 December 2020).

National Park Service. 2021. 3D fossilized redwood trio, Florissant Fossil Beds National Monument, Colorado. Online 3D model. Series: photogrammetry applications and examples. Article: paleontological modeling example—redwood trio, Florissant Fossil Beds National Monument. NPS Geologic Resources Division, Lakewood, Colorado. https://www.nps.gov/articles/paleontological-modeling-example-redwood-trio.htm (accessed 12 May 2021).

National Research Council. 2004. A geospatial framework for the coastal zone. The National Academies Press, Washington, DC.

National Wild and Scenic Rivers System. 2019. Explore designated rivers: California. Online information. US Fish and Wildlife Service, Burbank, Washington. https://www.rivers.gov/california.php.

Natoli, J. A., and R. J. Lillie. 2006. Shake, rattle, and roll—awaking the public's curiosity of geology via interpretation: a geology training manual for Redwood National and State Parks, California. Oregon State University, Department of Geosciences, Corvallis, Oregon.

Neuendorf, K. K. E., J. P. Mehl Jr., and J. A. Jackson. 2005. Glossary of geology. Fifth edition. American Geological Institute, Alexandria, Virginia.

Newberry, J. S. 1898. The later extinct floras of North America. Monograph 35. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/m35.

Nielsen, J. L., T. E. Lisle, and V. Ozaki. 1994. Thermally stratified pools and their use by steelhead in northern California streams. Transactions of the American Fisheries Society 123:613–626.

Nilsen, T. H., and S. H. Clarke Jr. 1987. Geological evolution of the late Cenozoic basins of northern California. Pages 15–30 *in* H. Schymiczek and R. Suchland, editors. Tectonics, sedimentation and evolution of the Eel River and other coastal basins in northern California. Miscellaneous Publication 37. San Joaquin Geological Society, San Joaquin, California.

North Coast Regional Water Quality Control Board. 2015. Water quality report card, Redwood Creek watershed (December 2015). State of California, North Coast Regional Water Quality Control Board, Santa Rosa, California. https://www.waterboards.ca.gov/northcoast/water_issues/programs/watershed_info/redwood_creek/.

North Coast Regional Water Quality Control Board. 2021. Redwood Creek watershed—hydrologic unit 107. Online information. State of California, North Coast Regional Water Quality Control Board, Santa Rosa, California. https://www.waterboards.ca.gov/northcoast/water_issues/programs/watershed_info/redwood_creek/ (accessed 25 January 2021).

Noss, R. F., editor. 2000. The redwood forest: history, ecology, and conservation of the coast redwoods. Island Press, Washington, DC.

Oakeshott, G. B. 1980. Tectonic history of the area north of San Francisco Bay. California Geology 33(12):266–273. http://maps.conservation.ca.gov/cgs/CGS_magazine.html [Note: Download file "33/12, P. 262 Cover captions."]

Ogle, B. A. 1953. Geology of the Eel River Valley area, Humboldt County, California. Bulletin 164. California Division of Mines, Sacramento, California.

Olson, D. F., D. F. Roy, and G. A. Walters. 1990. *Sequoia sempervirens* (D. Don) Endl. Redwood. Pages 541–551 *in* R. M. Burns and B. H. Honkala, editors. Silvics of North America, volume 1, conifers. Agriculture Handbook 654. USDA Forest Service, Washington DC. https://www.srs.fs.usda.gov/pubs/misc/ag_654/volume_1/sequoia/sempervirens.htm.

Orr, E. L., and W. N. Orr. 1999. Geology of Oregon. Fifth edition. Kendall/Hunt Publishing Company, Dubuque, Iowa.

Ozaki, K. 1991. Late Miocene and Pliocene floras in central Honshu, Japan. Kanagawa Prefectural Museum of Natural History, Odawara, Kanagawa Prefecture, Japan.

Ozaki, V. 1988. Geomorphic and hydrologic conditions for cold pool formation on Redwood Creek, California. Redwood National Park Research and Development Technical Report 24. Redwood National Park, Arcata Office, Arcata, California. https://irma.nps.gov/DataStore/Reference/Profile/55298.

Ozaki, V. 2014. Long-term trends in channel response and stream temperature in Redwood Creek. PowerPoint presentation. Redwood Creek Symposium, 10 December 2014, Orick, California. Redwood National Park, Crescent City, California.

Paleobiology Database. 2019. PBDB Navigator 1.0. Online database. University of Wisconsin, Department of Geoscience, Madison, Wisconsin. https://paleobiodb.org/navigator/ (accessed 8 August 2019).

Peale, A. C. 1907. Catalogue of the types and illustrated specimens of fossil plants in the Department of Geology, United States National Museum. Bulletin of the United States National Museum 53(2):83–350.

Peek, K. M., R. S. Young, R. L. Beavers, C. H. Hoffman, B. T. Diethorn, and S. Norton. 2015. Adapting to climate change in coastal national parks: estimating the exposure of park assets to 1 m of sea-level rise. Natural Resource Report NPS/NRSS/GRD/NRR—2015/961. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2221965.

Perry, R. W., J. C. Risley, S. J. Brewer, E. C. Jones, and D. W. Rondorf. 2011. Simulating daily water temperatures of the Klamath River under dam removal and climate change scenarios. Open-File Report OFR-2011-1243. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/ofr20111243.

Pessagno, E. A. Jr. 1973. Age and geologic significance of radiolarian cherts in the California Coast Ranges. Geology 1:153–156.

Pessagno, E. A. Jr. 1977. Upper Jurassic Radiolaria and radiolarian biostratigraphy of the California Coast Ranges. Micropaleontology 23:56–113.

Peterson, C. D., G. A. Carver, K. M. Cruikshank, H. F. Abramson, C. E. Garrison-Laney, and L. A. Dengler. 2011. Evaluation of the use of paleotsunami deposits to reconstruct inundation distance and runup heights associated with prehistoric inundation events, Crescent City, southern Cascadia margin. Earth Surface Processes and Landforms 36:967–980.

Peterson, C. D., J. J. Clague, G. A. Carver, and K. M. Cruikshank. 2013. Recurrence intervals of major paleotsunamis as calibrated by historic tsunami deposits in three localities: Port Alberni, Cannon Beach, and Crescent City, along the Cascadia margin, Canada and USA. Natural Hazards 68:321–336. doi:10.1007/s11069-013-0622-1.

Polenz, M., and H. M. Kelsey. 1999. Development of a late Quaternary marine terraced landscape during on-going tectonic contraction, Crescent City coastal plain, California. Quaternary Research 52(2):217–228.

Port, R. 2016. Golden Gate National Recreation Area, including Fort Point National Historic Site and Muir Woods National Monument: geologic resources inventory report. Natural Resource Report. NPS/NRSS/GRD/NRR—2016/1266. National Park Service. Fort Collins, Colorado. http://go.nps.gov/gripubs.

Redwood Creek Watershed Group. 2006. Redwood Creek integrated watershed strategy. Redwood Creek Watershed Group, Orick, California. https://irma.nps.gov/DataStore/Reference/Profile/627695.

Redwood National Park. 1985. Water resource management plan, Redwood National Park. National Park Service, Redwood National Park, Crescent City, California. https://irma.nps.gov/DataStore/Reference/Profile/135365.

Redwood National and State Parks. 2015. About the trees. Online information. Redwood National Park. National Park Service, Redwood National Park, Crescent City, California. Redwood National Park. https://www.nps.gov/redw/learn/nature/about-the-trees.htm (accessed 11 May 2021).

Redwood National and State Parks. 2019. Redwoods Rising. Online information. National Park Service, Redwood National and State Parks, Crescent City, California. https://www.nps.gov/redw/redwoodsrisingmain.htm (accessed 23 March 2020).

Reid, J. L., and R. S. Arthur. 1975. Interpretation of maps of geopotential anomaly for the deep Pacific Ocean. Journal of Marine Research 33:37–52.

Ricks, C. L. 1995. Effects of channelization on sediment distribution and aquatic habitat at the mouth of Redwood Creek, northwestern California. Chapter Q *in* K. M. Nolan, H. M. Kelsey, and D. C. Marron, editors. Geomorphic processes and aquatic habitat in the Redwood Creek basin, northwestern California. Professional Paper 1454. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/pp1454.

Ristau, D. 1979. Geologic map, Klamath 15-minute quadrangle (scale 1:62,500). Unpublished map. Title II Geologic Data Compilation Project. California Department of Forestry, Sacramento, California.

Robinson, D. T., K. R. Aalto, J. A. Barron, D. M. Erwin, and A. S. Jayko. 2001. Marine inundation of a late Miocene forest: stratigraphy and tectonic evolution of the Saint George Formation, Crescent City, California. California Geology 54(3):10–20. http://maps.conservation.ca.gov/cgs/CGS_magazine.html.

Rocha, A., R. Curry, and J. Stamm. 1999. Evidence of a Plio–Pleistocene forest in the Fort Ord area and its implications in determining local paleoclimate at the onset of the Pleistocene. Abstract. Geological Society of America Abstracts with Programs 31(7):462.

Rockman, M., M. Morgan, S. Ziaja, G. Hambrecht, and A. Meadow. 2016. Cultural resources climate change strategy. Cultural Resources, Partnerships, and Science and Climate Change Response Program, National Park Service, Washington, DC. https://www.nps.gov/subjects/climatechange/culturalresourcesstrategy.htm.

Ross, S. L., L. M. Jones, K. Miller, K. A. Porter, A. Wein, R. I. Wilson, B. Bahng, A. Barberopoulou, J. C. Borrero, D. M. Brosnan, J. T. Bwarie, E. L. Geist, L. A. Johnson, S. H. Kirby, W. R. Knight, K. Long, P. Lynett, C. E. Mortensen, D. J. Nicolsky, S. C. Perry, G. S. Plumlee, C. R. Real, K. Ryan, E. Suleimani, H. Thio, V. V. Titov, P. M. Whitmore, and N. J. Wood. 2013. The SAFRR tsunami scenario—improving resilience for California. Fact Sheet 2013–3081. US Geological Survey, Reston, Virginia. https://pubs.usgs.gov/fs/2013/3081/.

Roy, D. F. 1965. Redwood (*Sequoia sempervirens* [D. Don] Endl.). Pages 663–670 *in* H. A. Fowells, compiler. Silvics of forest trees of the United States. Agriculture Handbook 271. USDA Forest Service, Washington, DC.

Roy, D. F. 1966. Silvical characteristics of redwood (*Sequoia sempervirens* [D. Don] Endl.). Research Paper PSW-28. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California.

Ryan, H. F., R. von Huene, R. E. Wells, D. W. Scholl, S. Kirby, and A. E. Draut. 2012. History of earthquakes and tsunamis along the eastern Aleutian-Alaska megathrust, with implications for tsunami hazards in the California continental borderland. Chapter A *in* J. A. Dumolin and C. Dusel-Bacon, editors. Studies by the US Geological Survey in Alaska, 2011. Professional Paper 1795. US Geological Survey, Reston, Virginia. https://pubs.usgs.gov/pp/1795/a/.

Samylina, V. A. 1988. Arkagalinskaya stratoflora Severo-Vostoka Azii (Arkagalinskaya stratoflora of North-East Asia). Nauka Publishers, Leningrad, Leningrad Region, Russia. [In Russian.]

Santucci, V. L., and J. P. Kenworthy. 2009. Paleontological resource inventory and monitoring—Klamath Network. Natural Resource Technical Report NPS/NRPC/NRTR—2009/208. National Park Service, Fort Collins, Colorado. https://www.nps.gov/subjects/fossils/network-surveys.htm (permission needed to access report).

Santucci, V. L., J. Kenworthy, and R. Kerbo. 2001. An inventory of paleontological resources associated with National Park Service caves. Technical Report NPS/NRGRD/GRDTR-01/02. National Park Service, Geological Resources Division, Denver, Colorado. https://www.nps.gov/subjects/fossils/thematic-inventories.htm.

Save the Redwoods League. 2019. Coast redwoods. Online information. Save the Redwoods League, San Francisco, California. https://www.savetheredwoods.org/redwoods/coast-redwoods/ (accessed 12 August 2019).

Shervais, J. W. 2001. Birth, death, and resurrection: the life cycle of suprasubduction zone ophiolites. Geochemistry Geophysics Geosystems (G3): an electronic journal of the earth sciences, volume 2, paper number 2000GC000080. https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2000GC000080.

Shirley, J. C. 1940. The Redwoods of Coast and Sierra. University of California Press, Berkeley, California. https://www.nps.gov/parkhistory/online_books/shirley/index.htm.

Sillett, S. C., and R. Van Pelt. 2007. Trunk reiteration promotes epiphytes and water storage in an old-growth redwood forest canopy. Ecological Monographs 77:335–359.

Sliter, W. V. 1984. Foraminifers from Cretaceous limestone of the Franciscan Complex, northern California. Pages 149–162 *in* M. C. Blake Jr., editor. Franciscan geology of northern California. Field Trip Guidebook 43. Society of Economic Paleontologists and Mineralogists, Pacific Section, Upland, California.

Sloan, D. 2006. Geology of the San Francisco Bay region. California Natural History Guide Series No. 79. University of California Press, Berkeley and Los Angeles, California.

Sonnevil, R., R. Klein, D. A. Short, and W. Weaver. 1987. Forested block slides in the lower Redwood Creek basin, northwest California. IAHS-AISH Publication 165:145–46

Stewart, W. N., and G. W. Rothwell. 1993. Paleobotany and the evolution of plants, 2a. Cambridge University Press, Cambridge, England.

Stone, E. C., and R. B. Vasey. 1968. Preservation of coast redwood on alluvial flats. Science 159(3811):157–161.

Stone, L. 1992. Depositional/tectonic history of the Plio–Pleistocene Crescent City/Smith River, Del Norte County, California. Pages 51–54 *in* G. A. Carver and K. R. Aalto, editors. Field guide to the late Cenozoic subduction tectonics and sedimentation of northern coastal California. Field Guide GB-71. American Association of Petroleum Geologists, Pacific Section, Bakersfield, California. http://archives.datapages.com/data/pacific/data/087/087001/51_ps0870051.htm.

Stone, L. 1993. Pliocene-Pleistocene sedimentary and tectonic history of the Crescent City–Smith River region, Del Norte County, California. Thesis. Humboldt State University, Arcata, California.

Strahler, A. N. 1981. Physical geology. Harper & Row Publishers, New York, New York.

Strand, R. D. 1962. Geologic map of California: Redding sheet (scale 1:250,000). California Division of Mines and Geology, Sacramento, California. https://ngmdb.usgs.gov/Prodesc/proddesc_488.htm.

Sveshnikova, I. N. 1967. Late Cretaceous conifers of Soviet Union I, fossil conifers of the Viliuyian Depression. Paleobotanika 6:177–203. [In Russian].

Sveshnikova, I. N., and L. Y. Budantsev. 1969. Iskopaemye Flory Arktiki I. Nauka Publishers, Leningrad, Russia. [In Russian].

Swanston, D. N., R. R. Ziemer, and R. J. Janda. 1983. Influence of climate on progressive hillslope failure in Redwood Creek valley, northwestern California. Open-File Report 83-259. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/ofr83259.

Swanston, D. N., R. R. Ziemer, and R. J. Janda. 1995. Rate and mechanics of progressive hillslope failure in the Redwood Creek basin, northwestern California. Chapter E *in* K. M. Nolan, H. M. Kelsey, and D. C. Marron, editors. Geomorphic processes and aquatic habitat in the Redwood Creek basin, northwestern California. Professional Paper 1454. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/pp1454.

Tetzlaff, D., S. K. Carey, J. P. McNamara, H. Laudon, and C. Soulsby. 2017. The essential value of long-term experimental data for hydrology and water management. Water Resources Research 53:2598–2604. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2017WR020838.

The Diggings™. 2019. Mining in Del Norte County, California. Online information. The Diggings™, Chattanooga, Tennessee. https://thediggings.com/ (accessed 24 February 2021).

The White House Council on Environmental Quality. 2009. Interim report of the Interagency Ocean Policy Task Force. Office of the President of the United States, Interagency Ocean Policy Task Force, Washington, DC. https://digital.library.unt.edu/ark:/67531/metadc31145/.

US Bureau of Reclamation. 2011. Reservoir area management plan for the secretary's determination on Klamath River dam removal and basin restoration Klamath River, Oregon and California. Technical Report SRH-2011-19. Mid-Pacific Region, Sacramento, California. https://calisphere.org/item/ark:/86086/n26d5spb/.

US Environmental Protection Agency. 1998. Redwood Creek sediment, total maximum daily load. US Environmental Protection Agency, Region 9, San Francisco, California. https://www.waterboards.ca.gov/water_issues/programs/tmdl/records/region_1/2003/ref2094.pdf.

US Geological Survey. 2020 [date accessed]. California Seafloor Mapping Program. Online information. US Geological Survey, Pacific Coastal and Marine Science Center, Reston, Virginia. https://www.usgs.gov/centers/pcmsc/science/california-seafloor-mapping-program (accessed 16 March 2020).

US Geological Survey. 2021. US Quaternary faults. Online map viewer. US Geological Survey, Geologic Hazards Science Center, Golden, Colorado. https://usgs.maps.arcgis.com/apps/webappviewer/index.html?id=5a6038b3a1684561a9b0aadf88412fcf (accessed 19 May 2021).

Van Mantgem, P., M. A. Madej, J. Seney, and J. Deshais. 2013. Estimating ecosystem carbon stocks at Redwood National and State Parks. Park Science 30(1):20–26. https://irma.nps.gov/DataStore/DownloadFile/559854.

Varnes, D. J. 1978. Slope movement types and processes. Pages 11–33 *in* R. L. Schuster and R. J. Krizek, editors. Landslides: analysis and control. Special Report 176. Transportation and Road Research Board, National Academy of Sciences, Washington, DC.

Wagner, D. L., and G. J. Saucedo. 1987. Geologic map of the Weed quadrangle, California (scale 1:250,000). Regional Geologic Map Series Map RGM-4A (sheet 4). California Department of Conservation, Division of Mines and Geology, Sacramento, California. https://www.conservation.ca.gov/cgs/maps-data/rgm.

Watkins, J. D., R. B. Ballard, T. A. Beattie, L. Borrone, J. M. Coleman, A. D'Amato, L. Dickerson, P. G. Gaffney II, M. J. Hershman, P. L. Kelly, C. Koch, F. Muller-Karger, E. B. Rasmuson, A. A. Rosenberg, W. D. Ruckelshaus, and P. A. Sandifer. 2004. An ocean blueprint for the 21st century. US Commission on Ocean Policy, Washington, DC. https://govinfo.library.unt.edu/oceancommission/welcome.html.

Watkins, R. 1974. Molluscan paleobiology of the Wimer Formation, Del Norte County, California. Journal of Paleontology 48:1264–1282. https://www.jstor.org/stable/1303405?seq=1#metadata_info_tab_contents.

Watson, F. D., and J. E. Eckenwalder. 1993. Cupressaceae. Pages 399–422 *in* Flora of North America Editorial Committee, editors. Flora of North America north of Mexico, volume 2: pteridophytes and gymnosperms. Oxford University Press, Oxford, England.

Weatherbee, R., and B. Rasmussen. 2006. Clean-up and restoration of marijuana gardens. Regional funding request. Whiskeytown National Recreation Area, Whiskeytown, California. https://irma.nps.gov/DataStore/Reference/Profile/634261 (abstract only).

Wehmiller, J. F., G. L. Kennedy, and K. R. Lajoie. 1977. Amino acid racemization age estimates for Pleistocene dating of Pleistocene marine deposits in the Eureka–Fields Landing area, Humboldt County, California. Open File Report OF-77-517. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/ofr77517.

Welday, E. E., and J. W. Williams. 1975. Offshore surficial geology of California (scale 1:500,000). Map Sheet MS-26. California Division of Mines and Geology, Sacramento, California. https://ngmdb.usgs.gov/Prodesc/proddesc_74216.htm.

Welsh, H. W., G. R. Hodgson, and B. C. Harvey. 2001. Distribution of juvenile coho salmon in relation to water temperatures in tributaries of the Mattole River, California. North American Journal of Fisheries Management 21(3):464–470.

Wieczorek, G. F. and J. B. Snyder. 2009. Monitoring slope movements. Pages 245–271 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. https://www.nps.gov/subjects/geology/geological-monitoring.htm.

Williams, L. E. 2001. Irrigation of wine grapes in California. Department of Viticulture and Enology, University of California, Davis, California, and Kearney Agricultural Center, Parlier, California. https://www.yumpu.com/en/document/read/25179133/irrigation-of-winegrapes-in-california-by-larry-williams.

Wills, C. J. 2000. Landslides in the Highway 101 corridor between Wilson Creek and Crescent City, Del Norte County, California (scale 1:24,000). Special Report 184. California Geological Survey, Sacramento, California. https://www.conservation.ca.gov/cgs/reviews/highways.

Wilson, I. F. 1943. Geology of the San Benito quadrangle, California. California Journal of Mines and Geology 39(2):183–270.

Wilson, R. I., A. Barberopoulou, K. M. Miller, J. D. Goltz, and C. E. Synolakis. 2010. New maximum tsunami inundation maps for use by local emergency planners in the State of California, USA. Page 31 (abstract 14) *in* W. H. K. Lee, S. H. Kirby, and M. R. Diggles, compilers. Program and abstracts of the Second Tsunami Source Workshop: July 19–20, 2010. Open-File Report OFR-2010–1152. US Geological Survey, Tsunami Source Working Group, Reston, Virginia. http://pubs.usgs.gov/of/2010/1152/.

Wilzbach, M. A., and V. Ozaki. 2017. Fisheries and aquatic resources of Prairie Creek, Redwood National Park. Natural Resource Report NPS/REDW/NRR—2017/1492. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2243144.

Woodward-Clyde Consultants. 1980. Appendix B in Evaluation of the potential for resolving the geologic and seismic issues at the Humboldt Bay Power Plant Unit No. 3 (scale 1:24,000). Woodward-Clyde Consultants, San Francisco, California.

Worobiec, G., E. Worobiec, and J. Kasinski. 2008. Plant assemblages of the drill cores from the Neogene Ruja lignite deposit near Legnica (Lower Silesia, Poland). Acta Palaeobotanica 48:191–275.

Writing Group of Cenozoic Plants of China. 1978. Cenozoic plants from China, volume 3: fossil plants of China Science Press, Beijing, China. [in Chinese].

Wyrtki, K. 1975. Fluctuations of the dynamic topography in the Pacific Ocean. Journal of Physical Oceanography 5:450–459.

Young, R., and L. Norby. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado.

Zhang, J.-W., A. D'rozario, J. M. Adams, Y. Li, X.-Q. Liang, F. M. Jacques, T. Su, and Z.-K. Zhou. 2015. *Sequoia maguanensis*, a new Miocene relative of the coast redwood, *Sequoia sempervirens*, from China: implications for paleogeography and paleoclimate. American Journal of Botany 102(1):103–118.

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