National Park Service
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Natural Resource Stewardship and Science

Lewis and Clark National Historical Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2019/2023

ON THE COVER
Cape Disappointment and Cape Disappointment Lighthouse and mouth of the Columbia River in the Cape Disappointment State Park, Washington. Photography by user Adbar - Own work, utilized under the Creative Commons Attribution-Share Alike 4.0 International License (CC BY-SA 4.0), https://commons.wikimedia.org/w/index.php?curid=27188708 (accessed 14 August 2019).

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View of Cannon Beach and Haystack Rock taken from the picnic area in Ecola State Park. Photograph by Tom Purse, available at https://www.stateparks.com/ecola_state_park_in_oregon.html (accessed 14 August 2019).

Lewis and Clark National Historical Park

Geologic Resources Inventory Report

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

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Executive Summary

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

This report synthesizes discussions from a scoping meeting held in 2009 (see Appendix A). Chapters of this report discuss the geologic setting, distinctive geologic features and processes within Lewis and Clark National Historical Park, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the previously completed GRI map data. A poster (in pocket) illustrates these data.

On November 7, 1805, as the morning fog lifted, a shout went out from the Corps of Discovery. In his field notes, Captain William Clark would pen his immortal line, "Ocean in view! O! the joy." After more than 6,400 km (4,000 mi) from the mouth of the Missouri River, Captains Lewis and Clark and the Corps of Discovery had reached the Columbia River estuary. They would soon explore the north and south banks of the river and establish Fort Clatsop in northwestern Oregon. They would construct a salt works along the Oregon coast, and traverse Tillamook Head in search of a beached whale. Their legendary exploits during the winter of 1805–1806 are now interpreted in Lewis and Clark National Historical Park. Though originally comprised of only the Fort Clatsop site, Lewis and Clark National Historical Park now includes four sites in Oregon and three sites in Washington near the mouth of the Columbia River and within the Columbia River estuary. In addition to these seven sites within the park's legislative boundaries, nearby state parks may pursue management objectives and cooperative projects with Lewis and Clark National Historical Park.

Unbeknownst to the Corps of Discovery, they traversed roughly 50 million years of geologic history as they explored the Oregon coast and Columbia River estuary. Geologic features and processes from those 50 million years include the following:

- Eolian and coastal features. This general category includes sand dunes (geologic map unit **Qds**), beaches (**Qbs**), sea caves, sea stacks, headlands and cliffs, Clatsop Spit, tide pools, and the effect of the North Jetty on shoreline accretion at Cape Disappointment.
- Fluvial (river) features. In exploring the Netul River (now Lewis and Clark River) and other tributaries to the Columbia River, Lewis and Clark traversed floodplains (**Qf**), natural levees, and river terraces (**Qt**).
- Submarine features. Geologic features that were originally submerged are now exposed on land. These include turbidite deposits, which result from submarine density currents often associated with offshore earthquakes; invasive basalt; and basalt that erupted from submarine fissures. Lewis and Clark constructed Fort Clatsop on exposed turbidites of the Smuggler Cove Formation (**Tsc**) that are approximately 33.5 million–22 million years old. Ecola State Park on Tillamook Head consists of Grande Ronde Basalt (**Tgri**), a unit of basaltic lava flows that invaded the submarine Astoria Formation (**Tac**) about 16 million–14 million years ago. These basalt flows are part of the Columbia River Basalt Group, an extraordinary display of voluminous volcanic eruptions. Features found in the basalt at Middle Village–Station Camp, Cape Disappointment, Fort Columbia, and Dismal Nitch indicate submarine eruption of lava onto the ocean floor followed by rapid cooling.
- Landslides. Landslides in the Astoria Formation (**Tac**) and Crescent Formation (**Tc**) are ubiquitous throughout northwest Oregon and southwestern Washington. Triggered by earthquakes associated with the Cascadia Subduction Zone or from excessive precipitation, landslides continue to modify the landscape. They dominate the landscape of Ecola State Park and surround Fort Clatsop Visitor Center.
- Tectonic features. The Cascadia Subduction Zone has had a profound influence on the topography of northwestern Oregon and southwestern Washington. The collision of the oceanic tectonic plate with the western margin of North America produced numerous folds and faults. Accretion of submarine deposits and differential erosion has inverted the original topography so that formations such as the

Smuggler Cove Formation (**Tsc**), Astoria Formation (**Tac**), Grande Ronde Basalt (**Tgri**), and the Crescent Formation (**Tc**) that were originally deposited in submarine canyons and valleys now form highlands and cliffs along the coast. The rocks in these formations are more resistant to erosion than the surrounding semi-consolidated sedimentary rocks, which have eroded to now form lowland topography.
- Fossils. Fossils of primarily marine invertebrate fauna have been found in Tertiary formations throughout northwest Oregon and southwestern Washington. Although few fossils have been found within the units of Lewis and Clark National Historical Park, fossil-bearing formations occur in the park and may yet produce fossil material. Fossils help to interpret past depositional environments and paleoclimate, as well as the age of the deposits.

The geologic resource management issues and hazards associated with the park may be categorized as:

- Hazards associated with the Cascadia Subduction Zone. These hazards include earthquakes, tsunamis, liquefaction, and volcanic activity.
- Landslide hazards. Landslides are prevalent throughout the Pacific Northwest. Most landslides in Lewis and Clark National Historical Site are caused by saturation of slopes by abundant precipitation.
- Flooding. Flooding causes extensive damage throughout Washington and Oregon. Fort Clatsop, Netul Landing, and parts of Seaside reside within the effective FEMA 100-year flood area.
- Paleontological inventory. Although no paleontological specimens are curated by Lewis and Clark National Historical Park, several of the Tertiary (Neogene and Paleogene) formations in the park and surrounding are contain fossils, especially the Astoria Formation (**Tac**). Recent land acquisitions over the past several years have resulted in even more strata within the park that may contain fossils. A paleontological inventory and monitoring program, especially in coordination with archeological excavations and cultural artifacts, offers the park opportunities for field surveys, education, interpretation and future scientific research.
- Cave inventory. Lewis and Clark National Historical Park is not on the NPS list of parks with cave and karst resources. However, sea caves have formed in the bedrock cliffs of the Crescent Formation (**Tc**) at Cape Disappointment. The presence of the caves offers the park an opportunity to develop a cave management program.
- Issues associated with global climate change. Competition for available water resources is expected to increase as climate changes. Landslides generated by excessive precipitation, flooding, sea level rise, and coastal erosion present challenges to resource management that will intensify as climate changes.
- Issues associated with coastal and shoreline engineering. Coastal engineering projects at the mouth of the Columbia River impact units in the park. These projects include jetty repair and maintenance, shoreline stabilization along the Columbia River, dredging, and beach nourishment.
- Issues associated with hydrocarbon exploration. Although economic quantities of gas have been discovered in Oregon, the hydrocarbon potential in Lewis and Clark National Historical Park is extremely low. However, strata within the Astoria Formation (**Tac**) appear to be potential offshore hydrocarbon reservoirs.

Lewis and Clark National Historical Park captures a West Coast geologic history that includes: (1) the evolution of the Cascadia Subduction Zone, (2) the construction of the Astoria Basin, (3) the eruption of vast quantities of basalt, and (4) sea level rise following the Pleistocene ice ages. The oldest rocks in the Lewis and Clark National Historical Park are found in the cliffs of Cape Disappointment, Fort Columbia, and Middle Village–Station Camp where roughly 50-million-year-old submarine basalt now forms the cliffs overlooking the Pacific Ocean and Columbia River estuary. The rocks and sediments in Lewis and Clark National Historical Park document the growth of the Cascadia Subduction Zone, rivers of basalt that flowed through the Columbia River Gorge and out to sea, ice age climates, and a modern landscape formed by earthquakes, landslides, and modern coastal and fluvial processes.

This GRI report was written for resource managers to support science-informed decision making. It may also be useful for interpretation. This report is supported by a GRI-compiled geologic map of Lewis and Clark National Historical Park. The source maps for the GRI-compiled geologic map were published by the Oregon Department of Geology and Mineral Industries (DOGAMI) and the US Geological Survey (USGS). The source map data are available in ESRI ArcGIS format (lewi_geology.mxd) and a partial data set (no point features) is available in Google Earth-compatible format (lewi_geology.kmz). A poster (in pocket) illustrates the data over shaded relief imagery. The Geologic Mad Data section of this report contains additional information about the GRI GIS data.

Products and Acknowledgments

The NPS Geologic Resources Division partners with the Colorado State University Department of Geosciences to produce GRI products. The US Geological Survey and Oregon Department of Geology and Mineral Industries developed the source maps. US Geological Survey and NPS staff reviewed GRI content. This chapter describes GRI products and acknowledges contributors to this report.

GRI Products

The GRI team undertakes three tasks for each park in the Inventory and Monitoring program: (1) conduct a scoping meeting and provide a summary document, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report (this document). These products are designed and written for nongeoscientists.

Scoping meetings bring together park staff and geologic experts to review and assess available geologic maps, develop a geologic mapping plan, and discuss geologic features, processes, and resource management issues that should be addressed in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to GIS data in accordance with the GRI data model. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the GRI report. The GRI team conducts no new field work in association with their products.

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

Additional information regarding the GRI, including contact information, is available at the GRI program website (http://go.nps.gov/gri).

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Additional thanks to Trista Thornberry-Ehrlich (Colorado State University) for producing many of the graphics in this report.

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List of Abbreviations

CRBG: Columbia River Basalt Group

CSZ: Cascadia Subduction Zone

CVO: USGS Cascades Volcano Observatory

DOGAMI: Oregon Department of Geology and Mineral Industries

GMSL: Global mean sea level

GRI: NPS Geologic Resources Inventory

MCR: Mouth of the Columbia River

NCCN: NPS North Coast and Cascades Network

NHP: National Historical Park

NOAA: National O ceanic and Atmospheric Administration

NPS: National Park Service

RSL: Relative Sea Level

USACE: US Army Corps of Engineers

USGS: US Geological Survey

VHP: USGS Volcano Hazards Program

Geologic map units throughout the report are referenced in this style: **Tsm**. The capital letter corresponds to the age of the map unit (T = Tertiary Period; see figure 2 for complete list of geologic ages) and the following lowercase letter indicate the map unit name (sm= Sandstone at Megler). Full unit descriptions are available in the lewi_geology.pdf, which is included in the GRI GIS data.

Table 1. Ownership or management of units within Lewis and Clark NHP and nearby state parks.

Information extracted from the draft Natural Resource Condition Assessment, courtesy of Carla Cole and Chris Clatterbuck (Lewis and Clark NHP).

1 Cape Disappointment State Park's visitor and maintenance functions are managed by Washington State Parks with projects falling on NPS land subject to NEPA, NHPA, and other federal laws. NPS conducts natural resource inventories and monitoring as well as collaborates with Washington State Parks on natural resource projects.

2 NPS owns and manages 154 acres. Washington Department of Transportation owns and operates the safety rest area, Pacific County owns 5 acres. The State of Washington owns the tidelands.

3 NPS owns and manages 8 acres. As of publication, discussions are still on-going for the possible acquisition or easement of 347 privately owned acres. The State of Washington owns the tidelands.

4 Private landowners own approximately 37 acres within the Fort Clatsop Unit.

Unit	Owner or Manager
Cape Disappointment State Park (within park legislative boundary) – WA	Washington State Parks and Recreation Commission, NPS, US Army Corps of Engineers[1]
Cape Disappointment State Park (outside park legislative boundary) –WA	Washington State Parks and Recreation Commission
Clark's Dismal Nitch – WA	NPS, State of Washington, Pacific County[2]
Middle Village-Station Camp – WA	NPS, private landowner, State of Washington[3]
Fort Columbia State Park – WA	Washington State Parks and Recreation Commission
Fort Clatsop Unit – OR	NPS, private landowners[4]
Salt Works – OR	NPS
Sunset Beach State Recreation Area – OR	Oregon Parks and Recreation Department
Yeon Property – OR	NPS

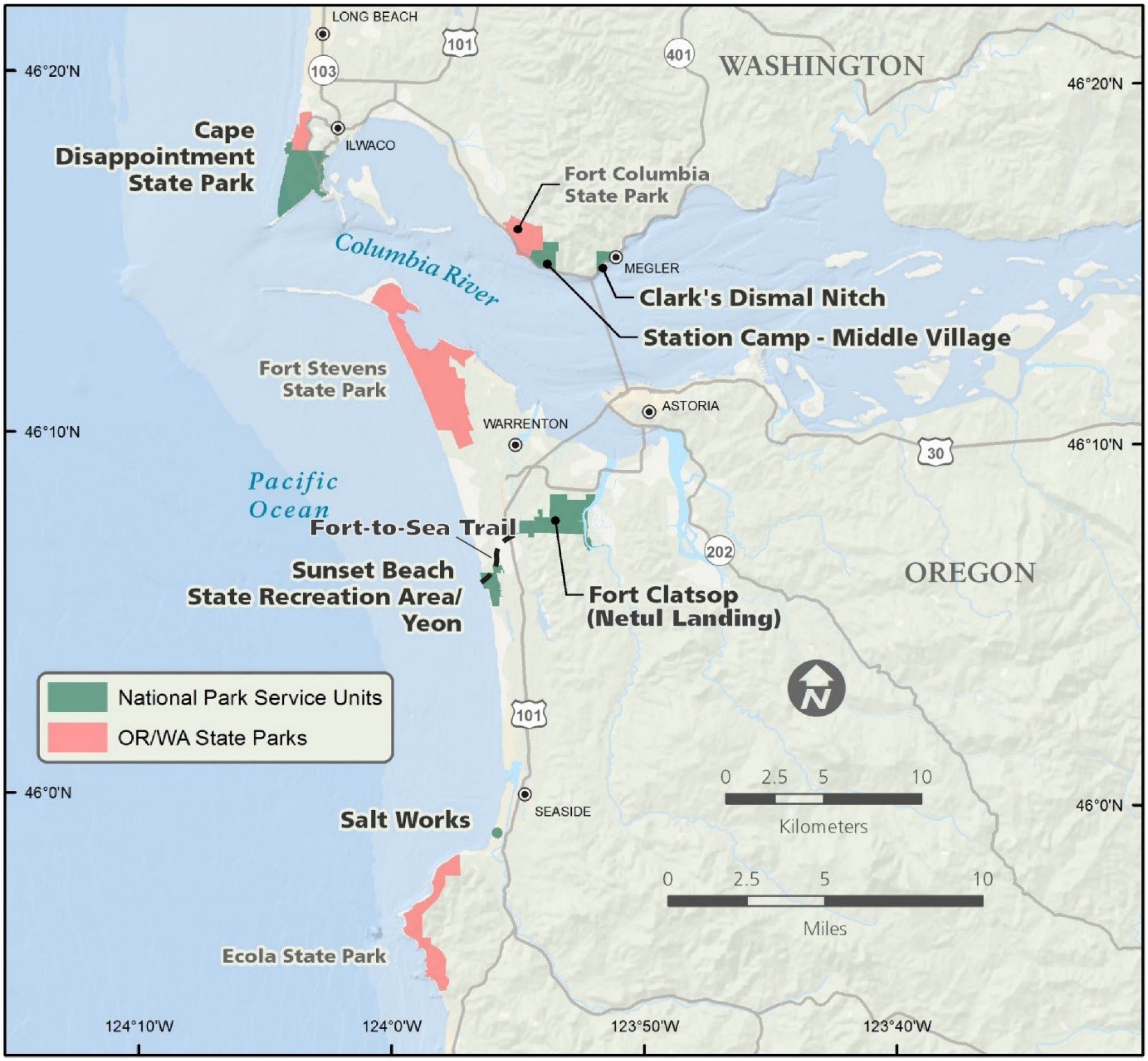


Figure 1. Location map of Lewis and Clark NHP and nearby state parks.
From north-to-south NPS units include portions of Cape Disappointment State Park (WA), Station Camp-Middle Village (WA), Clark's Dismal Nitch (WA), Fort Clatsop (OR), Sunset Beach State Recreation Area/ Yeon property (OR), and Salt Works (OR). Nearby state parks that sometimes pursue share management objectives and cooperative projects with the NPS include, from north to south, portions of Cape Disappointment State Park (WA), Fort Columbia State Park (WA), Fort Stevens State Park (OR), and Ecola State Park. The Fort to Sea Trail connects Fort Clatsop with Sunset Beach State Recreation Area. Netul Landing is located in the southernmost area of the Fort Clatsop unit, along the Lewis and Clark River. Table 1 (previous page) lists the NPS units and nearby state parks, as well as the respective management agency. NPS map courtesy of Carla Cole and Chris Clatterbuck (Lewis and Clark NHP). Netul Landing and Fort to Sea Trail annotations added by Michael Barthelmes (Colorado State University).

Geologic Setting and Significance

This chapter describes the regional geologic setting of Lewis and Clark National Historical Park and summarizes connections among geologic resources, other park resources, and park stories.

Park Establishment and Significance

By October 23, 1805, Lewis and Clark and the Corps of Discovery had traveled down the Columbia River to the confluence with the Deschutes. For the next 88 km (55 mi), beginning with Great Falls (Celilo Falls), the expedition would portage and lower their canoes using rope made of elk skin through dangerous cataracts and rapids (currently drowned beneath dam reservoirs) that plunged through the narrow Columbia River Gorge (Ronda 1984; Ambrose 1996). Towering 1,000-m (3,000-ft) cliffs of 16 million-year-old volcanic lava flows bordered the gorge. Clark would revisit these solidified lava flows when he traversed Tillamook Head to reach a beached whale on Cannon Beach. At Cape Disappointment, Lewis and Clark would find even older volcanic deposits juxtaposed against a coastline of recently constructed sand dunes. Unbeknownst to the expedition, they encountered evidence of three world-class events that define the geologic framework of Oregon and Washington: (1) the subduction of the Juan de Fuca tectonic plate beneath the North American continent, (2) the extraordinary outpouring of Columbia River basalt, and (3) the Pleistocene ice ages and the colossal Glacial Lake Missoula floods. Today, this evidence is preserved within Lewis and Clark National Historical Park (NHP).

Established in 2004, Lewis and Clark NHP "preserves, restores, and interprets key historic, cultural, scenic, and natural resources throughout the lower Columbia River area associated with the Lewis and Clark Expedition's arrival at and exploration of the Pacific coast, and commemorates the 1805–1806 winter encampment at Fort Clatsop" (NPS 2015, p. 5). The natural resources preserved in the park include a myriad of geologic features associated with fluvial (river), coastal, volcanic, seismic, and glacial processes. Paleontological resources in formations found in the park help identify past environmental conditions. Within the last 10,000 years, the interaction between climate and the geologic landscape has produced an array of diverse ecosystems that include rainforest, freshwater wetlands, tidal estuaries, and coastal prairies. These ecosystems are considered to be fundamental resources in the park, resources "essential to achieving the purpose of the park and maintaining its significance" (NPS 2015, p. 7).

The historical park is administered through a cooperative venture involving the National Park Service and the states of Oregon and Washington. Though originally comprised of only the Fort Clatsop site, Lewis and Clark NHP now in includes four sites totaling 738 ha (1,824 ac) in Oregon's Clatsop County and three sites totaling 575 ha (1421 ac) in Washington's Pacific County (fig. 1) (Bakker et al. 2010). In addition to the seven sites within the park's legislative boundaries, there are nearby state parks (fig. 1) that sometimes pursue shared management objectives and cooperative projects with Lewis and Clark NHP. The national and state park units that ring the mouth of the Columbia River (MCR) are within the Columbia River estuary and extend for 64 km (40 mi) along the Pacific coast from Long Beach, Washington, to Cannon Beach, Oregon (fig. 1). In addition to fundamental geologic resources, the park contains archeological evidence that documents the dramatic changes that occurred to the indigenous Chinook and Clatsop tribes following their introduction to European, Asian, and other newcomers to the area. Scientific observation and documentation of park resources continues to be a fundamental value, encouraged through the park's research and educational programs (NPS 2015).

Geologic Setting

According to Ian Madin, chief scientist for the Oregon Department of Geology and Mineral Industries (DOGAMI), the three world-class events that are responsible for the geologic framework of Washington and Oregon include: (1) subduction, (2) Columbia River basalt flows, and (3) glaciation (see Graham 2010). Modern day fluvial, coastal, and tectonic processes, along with anthropomorphic activity, have continued to shape the landscape of northwestern Oregon and southwestern Washington.

Subduction

Oblique collision between the North American and Juan de Fuca tectonic plates in the Eocene (fig. 2) caused the denser oceanic Juan de Fuca crust to be driven beneath the North American continent, forming the Cascadia Subduction Zone (CSZ) off the Pacific Northwest coast (fig. 3). The CSZ extends for 1,000 km (620 mi) from Vancouver Island to Cape Mendocino, California, making it one of the world's largest subduction zones. The subduction zone was once considered to be a continuous fault line, but a 13-year study published in 2012 documented a partially segmented subduction zone (Goldfinger et al. 2012). In general, three regions characterize the subduction zone: (1) an offshore trench that marks the contact between

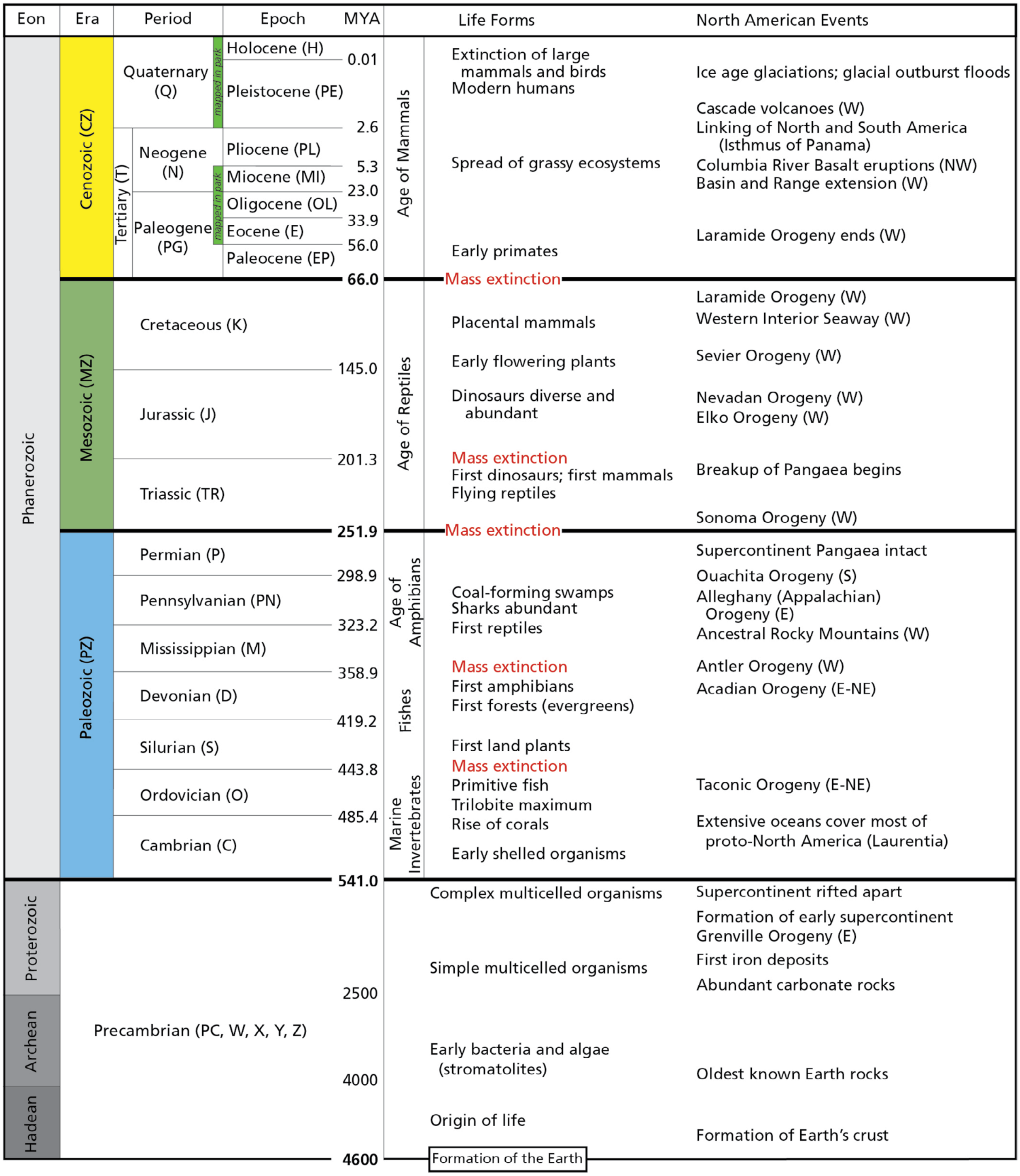
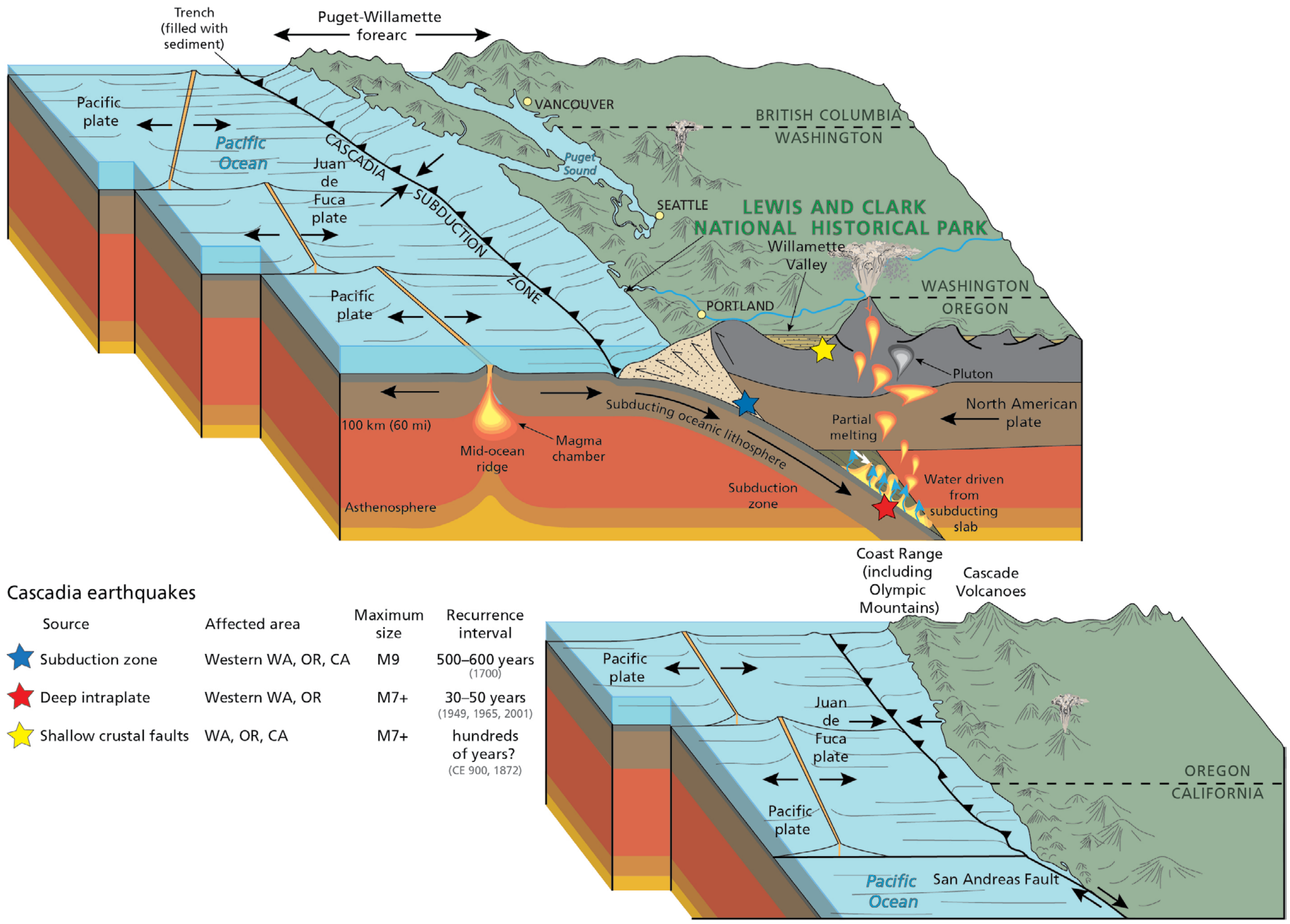


Figure 2. Geologic time scale.
The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. The green bar indicates the ages of geologic units that are mapped within Lewis and Clark NHP, which are, from oldest to youngest, the Eocene, Oligocene, Miocene, Pleistocene, and Holocene. The time period from the Eocene through the Miocene spans from 56 million to 5.3 million years ago. The Pleistocene and Holocene spans from 2.6 million years ago to present day. GRI map abbreviations for each time division are in parentheses. The Eocene, Oligocene, and Miocene are part of the Tertiary and are indicated with a "T" on GRI map units. The Pleistocene and Holocene are part of the Quaternary and are indicated with a "Q." Compass directions in parentheses indicate the regional locations of events. Boundary ages are millions of years ago (MYA). National Park Service graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale, accessed 27 February 2017).



Cascadia earthquakes

Source	Affected area	Maximum size	Recurrence interval
Subduction zone (blue star)	Western WA, OR, CA	M9	500–600 years (1700)
Deep intraplate (red star)	Western WA, OR	M7+	30–50 years (1949, 1965, 2001)
Shallow crustal faults (yellow star)	WA, OR, CA	M7+	hundreds of years? (CE 900, 1872)

Figure 3. Illustration of the Cascadia Subduction Zone.
Lewis and Clark NHP is located within the forearc basin of the subduction zone. At the convergent boundary, the denser Juan de Fuca Plate subducts beneath the North American Plate, causing earthquakes. A deep Juan de Fuca plate earthquake occurred in 2001. Rocks melt to form magma, which rises to the surface to form volcanoes. Once considered to be a continuous subduction zone fault, as drawn, the Cascadia Subduction Zone is now known to be partially segmented into a northern and southern zone. CE: Common Era (preferred to “AD”). Diagram modified by Trista Thornberry-Ehrlich (Colorado State University) from the Pacific Northwest Seismic Network (PNSN) (https://pnsn.org/outreach/earthquakesources/csz; accessed 1 July 2017) and the Oregon Office of Emergency Management (http://www.oregon.gov/oem/hazardsprep/Pages/Cascadia-Subduction-Zone.aspx; accessed 1 July 2017).

the two lithospheric plates, (2) a basin (forearc basin) that forms between the trench and a volcanic arc, and (3) a volcanic arc that forms above the down-going slab of oceanic crust. The Cascade Range is the most recent in a series of volcanic arcs associated with the CSZ (fig. 3). Within the park, the Crescent Formation (geologic map unit **Tc**), basalt breccia and flows at Fort Columbia (**Tbr**, **Tbf**), Sandstone at Megler (**Tsm**), siltstone at Shoalwater Bay (**Tsb**), the Sager Creek Formation (**Ts**), the Lincoln Creek Formation (**Tlc**) and the Smuggler Cove Formation (**Tsc**) represent sediments deposited in the forearc basin and subsequently deformed as they were accreted to the continental margin (table 2).

The western margin of North America consists of a series of crustal blocks, including, from north to south, the Vancouver Island, Washington, Oregon, and the Sierra Nevada crustal blocks. The blocks are separated from each other by complex zones of normal and reverse faults (fig. 4). Reverse faults commonly border the western margins of uplifts. The Sierra Nevada block in California is being driven north–northwest into the Oregon block, causing the Oregon Coast Range to rotate clockwise and resulting in a right-lateral (dextral) shearing motion that pushes the Oregon block into Washington State (fig. 5; Wells et al. 1998; McCaffrey et al. 2007; Evarts et al. 2009; Pacific Northwest Seismic Network 2017). The oblique, clockwise rotation of the

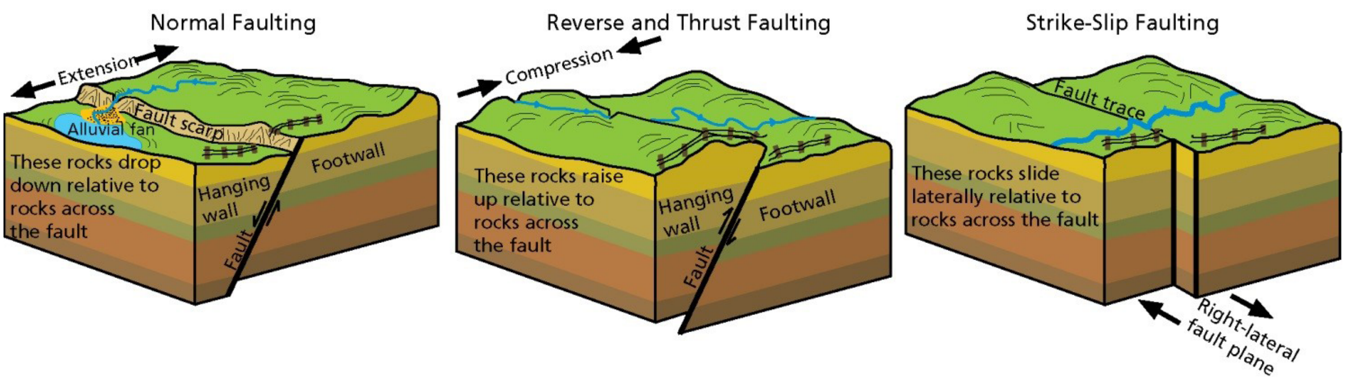


Figure 4. Schematic illustrations of fault types.
Movement occurs along a fault plane. Footwalls are below the fault plane and hanging walls are above. In a normal fault, such as those in northwestern Oregon, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging wall up relative to the footwall. A thrust fault is similar to a reverse fault but has a dip angle of less than 45°. In a strike-slip fault, the relative direction of movement of the opposing plate is lateral. When movement across the fault is to the right, it is a right-lateral (dextral) fault, as illustrated above. When movement is to the left, it is a left-lateral (sinistral) fault. A strike-slip fault between two plate boundaries is called a transform fault. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Table 2. Stratigraphic column of the geologic units within Lewis and Clark National Historical Park.

The Holocene and Pleistocene epochs are in the Quaternary Period, the Miocene belongs to the Neogene Period, and the Oligocene and Eocene are part of the Paleogene Period. Refer to figure 1 and table 1 for the location and management agency of park units.

Epoch	Map Unit (symbol)	Geologic Description	Park Sites and Nearby State Parks
Holocene	Beach sand (**Qbs**)	Moderately well-sorted, fine- to medium-grained quartz and feldspar sand with dark bands (laminae) of magnetite, ilmenite, and other heavy minerals.	Cape Disappointment Fort Stevens Fort to Sea Trail Sunset Beach Salt Works
	Fluvial and estuarine deposits (**Qf**)	Unconsolidated clay, silt, sand, and gravel along rivers and streams.	Middle Village–Station Camp
	Alluvium (**Qal**)	Unconsolidated floodplain deposits of clay, silt, sand, and basalt gravel.	Fort Clatsop Netul Landing
Holocene and Pleistocene	Dune sand (**Qds**)	Well sorted, fine grained, quartz and feldspar sand with heavy mineral laminae. Includes peat and lacustrine mud deposits.	Fort Stevens Fort Clatsop Fort to Sea Trail Sunset Beach
	Terrace deposits (**Qt**)	Alluvial silt, sand, and semi-consolidated basalt gravel.	Fort Clatsop
Miocene	Astoria Formation Cannon Beach Member (**Tac**, **Tac1**)	**Tac**. Well-bedded sequence of laminated to massive micaceous mudstone and sandstone. **Tac1**. Slope channel sandstone. Rhythmically thin-bedded feldspathic sandstone and mudstone.	Ecola
	Columbia River Basalt Group Grande Ronde Basalt, intrusive basalt (**Tgri**)	Invasive sills as much as 200 m (650 ft) thick, dikes, irregular bodies of massive to columnar-jointed basalt. Primarily fine-grained texture. K–Ar ages range from 14.0±2.7 million years ago to 15.9±0.3 million years ago.	Ecola

Table 2 (continued). Stratigraphic column of the geologic units within Lewis and Clark National Historical Park.

Epoch	Map Unit (symbol)	Geologic Description	Park Sites and Nearby State Parks
Miocene, Oligocene, and Eocene	Smuggler Cove Formation Undivided (**Tsc**)	Bioturbated tuffaceous claystone and siltstone with a few volcanic and glauconitic sandstone beds and volcanic tuffs.	Ecola
	Smuggler Cove Formation Upper Member (**Tsc2**)	Tuffaceous siltstone and sandy siltstone. A 10–15 m (33–39 ft) thick bed of glauconitic sandstone separates **Tsc1** from **Tsc2**.	Fort Clatsop
	Smuggler Cove Formation Lower Member (**Tsc1**)	Thick-bedded tuffaceous silty claystone.	Fort Clatsop
	Lincoln Creek Formation (**Tlc**)	Dark-gray to olive-gray, tuffaceous siltstone and sandstone with large-scale soft-sediment deformation and concretions.	Cape Disappointment
Eocene	Siltstone at Shoalwater Bay (**Tsb**)	Dark-gray, thin-bedded, laminated, tuffaceous siltstone with thin tuff beds, minor thin-bedded feldspathic sandstone, and calcareous concretions.	Cape Disappointment
	Sandstone at Megler (**Tsm**)	Light-gray, thin- to thick-bedded very fine to medium-grained micaceous feldspathic sandstone and interbedded siltstone.	Middle Village–Station Camp Dismal Nitch
	Basalt lapilli breccia and flows (**Tbr**)	Basalt lapilli (ejected rock fragments) tuff, basalt breccia, and basalt sandstone and conglomerate. Vesicles cemented with calcite and zeolite. Local large plagioclase crystals as much as 13 cm (5 in) long. Interbedded with **Tsm** at Megler.	Fort Columbia Middle Village–Station Camp Dismal Nitch
	Pillow basalt flows (**Tbf**)	Fine-grained pillow and columnar-jointed basalt and breccia containing vesicles and fractures filled with zeolite, calcite, and quartz. Submarine alteration of glass to green smectite clays.	Dismal Nitch
	Crescent Formation (**Tc**)	Pillowed, columnar-jointed, and massive basalt, fine- to medium-grained with some phenocrysts (large crystals) of plagioclase, pyroxene, and olivine.	Cape Disappointment Fort Columbia Middle Village–Station Camp

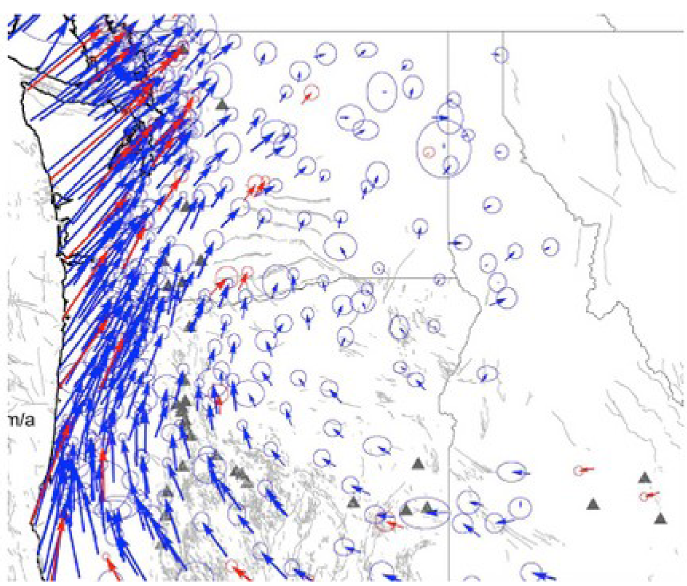


Figure 5. Vector map showing the direction of movement of tectonic blocks in the Pacific Northwest. The blue arrows indicate a clockwise rotation of western Oregon into the state of Washington. Ellipses in the Cascade Range indicate west–east extension, with the long axis in the direction of extension. The Puget Lowland was compressed and warped into a series of alternating uplifted and down warped terrain. Diagram from the Pacific Northwest Seismic Network, https://pnsn.org/outreach/about-earthquakes/plate-tectonics (accessed 3 July 2017).

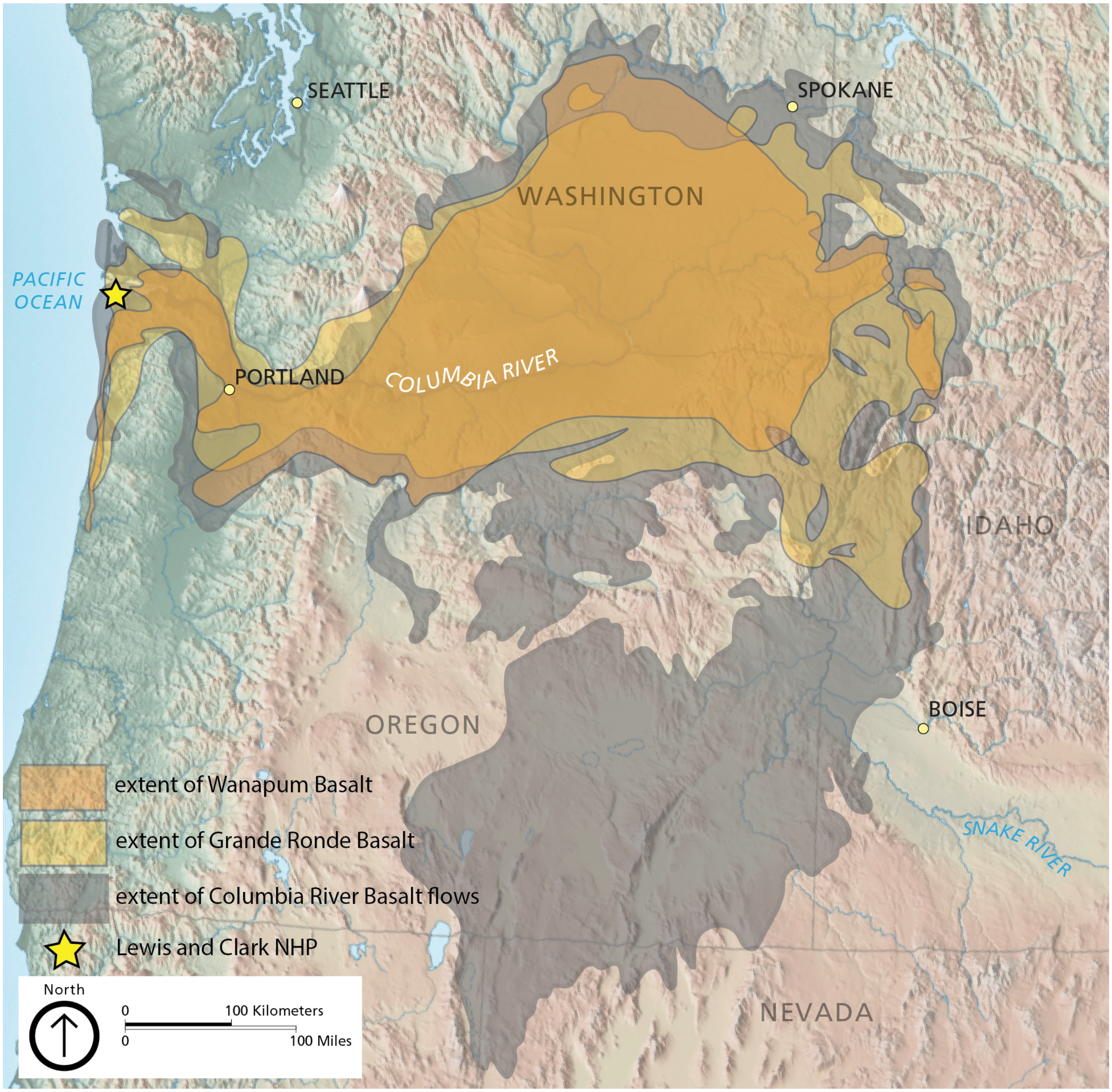


Figure 6. Map showing the distribution of the Columbia River Flood Basalt.
During the middle Miocene, over 300 high-volume individual basaltic lava flows and countless small flows poured from fissures that opened in the eastern portion of the Pacific Northwest crust and flooded roughly 160,000 km2 (63,000 mi2) of the Pacific Northwest. These lava flows accumulated into a thickness of over 1,800 m (6,000 ft) and collectively formed the Columbia River Basalt Group. Map by Trista Thornberry-Ehrlich and Michael Barthelmes (Colorado State University) with information from Alt and Hyndman (1995, http://geology.isu.edu/Digital_Geology_Idaho/Module10/mod10.htm; accessed 29 July 2013). Base map by Tom Patterson (NPS), available at http://www.shadedrelief.com/physical/index.html (accessed 15 August 2019).

Oregon block created the Astoria Basin, which includes the Oregon units of Lewis and Clark NHP (Niem and Niem 1985; Niem et al. 1985). The east–west trending fault that separates the older rocks in southwestern Washington, which are undergoing compression, from the younger rocks in northwestern Oregon, which are undergoing extension, lies beneath the Columbia River.

Columbia River Basalts

The lava flows that Lewis and Clark encountered in the Columbia River Gorge represent the second world-class event. These flows are part of the Columbia River Basalt Group (CRBG) (table 2). Originating about 16 million years ago from fissures in the eastern Oregon and Washington crust, basaltic lava flowed into a broad Columbia River valley, covering roughly 164,000 km^2 (63,000 mi^2) of the Pacific Northwest (Evarts et al. 2009; Madin 2009). Humans have never witnessed flood basalts as extensive as these. Flows also spread over portions of Idaho, Nevada, and California (fig. 6). Many of the individual flows contained thousands of cubic kilometers of lava (Tolan et al. 1989). The basalt was extremely fluid, pouring out of the fissures and reaching the Pacific in just 7 days (Graham 2010). In a unique process, dense basaltic lava that flowed 560 km (350 mi) over land then burrowed into less dense submarine sediments for another 50 km (30 mi). The term "invasive lava" has been coined to describe this unique process. Similar flows have been found as far south as Newport, Oregon. At least 20 times, voluminous lava flows about 30 m (100 ft) deep and 480 km (300 mi) long filled the Columbia River valley and entered the ocean near Astoria (see summaries in Graham 2010, 2014, and 2019). The Grande Ronde Basalt (**Tgri**) that Clark traversed in Ecola State Park represents the CRBG in the study area (table 2). Originally submarine deposits, the basalt and overlying Astoria Formation have been accreted to the Pacific Northwest coastline and uplifted to form Tillamook Head.

Pleistocene Glaciation

The third world-class event to affect western Oregon and Washington was the Pleistocene Ice Age (fig 2). About 12,000 years ago, the coast was 80 km (50 mi) offshore relative to today's coastline. In Idaho, the extensive Glacial Lake Missoula formed behind ice dams. When the ice dams failed, cataclysmic floods cascaded through the Columbia River Gorge to the sea (see Graham 2014, 2019) for details and references on the colossal Glacial Lake Missoula floods as recorded at Whitman Mission and Fort Vancouver National Historic Sites). As the glaciers melted, sea level rose and the Columbia River valley became an extensive estuary. River and marine sediments buried the glacial deposits. The MCR represents a rare estuarine/fluvial system that has developed within the active tectonic margin of western North America. Today's coastal landforms such as dune ridges (**Qds**), spits, beaches (**Qbs**), and estuaries (**Qf**) represent post-glacial features that continue to modify the landscape as sea level rises (table 2).

A regional stratigraphy consisting of marine sedimentary rocks, lava from the CRBG, and young Quaternary deposits resulted from these three world-class events. In Washington, a regional unconformity separates Quaternary deposits from middle Miocene CRBG and Eocene tuffs and basalts. Park units in Oregon sit atop the zone where CRBG lava is transitional from subaerial basalt flows to basalt that flowed into the ocean and became submarine basalt flows.

The Modern Landscape

All of the units in Lewis and Clark NHP are influenced by the Columbia River and its estuary. Within the borders of the United States, only the Mississippi and Ohio rivers have higher discharges than the Columbia River, which discharges at an average rate of 7,730 m^3/s (273,000 ft^3/s). For comparison, the Mississippi River discharges at an average of 16,800 m^3/s (593,000 ft^3/s), while the Ohio River discharges at an average of 7,971 m^3/s (281,500 ft^3/s). Prior to the dams along the Columbia River and its tributaries, roughly 4.6 million m^3 (162 million ft^3) of sediment was transported to the MCR each year. The sediment was distributed along the coast by the Columbia River littoral cell (ocean currents running along the shoreline), which is an area extending ~165 km (~100 mi) between Tillamook Head, Oregon, and Point Grenville, Washington (Allan et al. 2009). The Columbia River littoral cell consists of four sub-cells separated by estuary entrances of the Columbia River, Willapa Bay, and Grays Harbor (fig. 7). These cells form gently sloping beaches of sand derived from the Columbia River. The nearshore zone consists of broad surf zones with multiple sandbars. Dune fields and swales form landward of the beaches. Sea cliffs anchor the coast at Tillamook Head, Cape Disappointment, and the northern half of the North Beach sub-cell (fig. 7). Because they form along an active tectonic coastal margin, the beaches have experienced episodic erosion and sudden 1–2 m (3–7 ft) subsidence events associated with large earthquakes (Allan et al. 2009).

The Columbia River littoral cell is known for its significant wave heights and severe winter weather. Average annual wave heights are 2.2 m (7.2 ft), but winter storms can generate waves up to 15 m (50 ft) high (Komar 1992; Allan and Komar 2002; Allan et al. 2009). High, long-period waves averaging ~3 m (~10 ft) in height every 12–13 seconds, high water levels, and waves approaching from the west-southwest characterize the winter months. Summer (May through August) conditions consist of smaller waves, lower water levels, and wind and waves from the west-northwest. Water levels are ~30 cm (~12 in) higher in winter than during summer months. In addition, the higher than normal water levels and increased storm frequency associated with strong El Niño events may

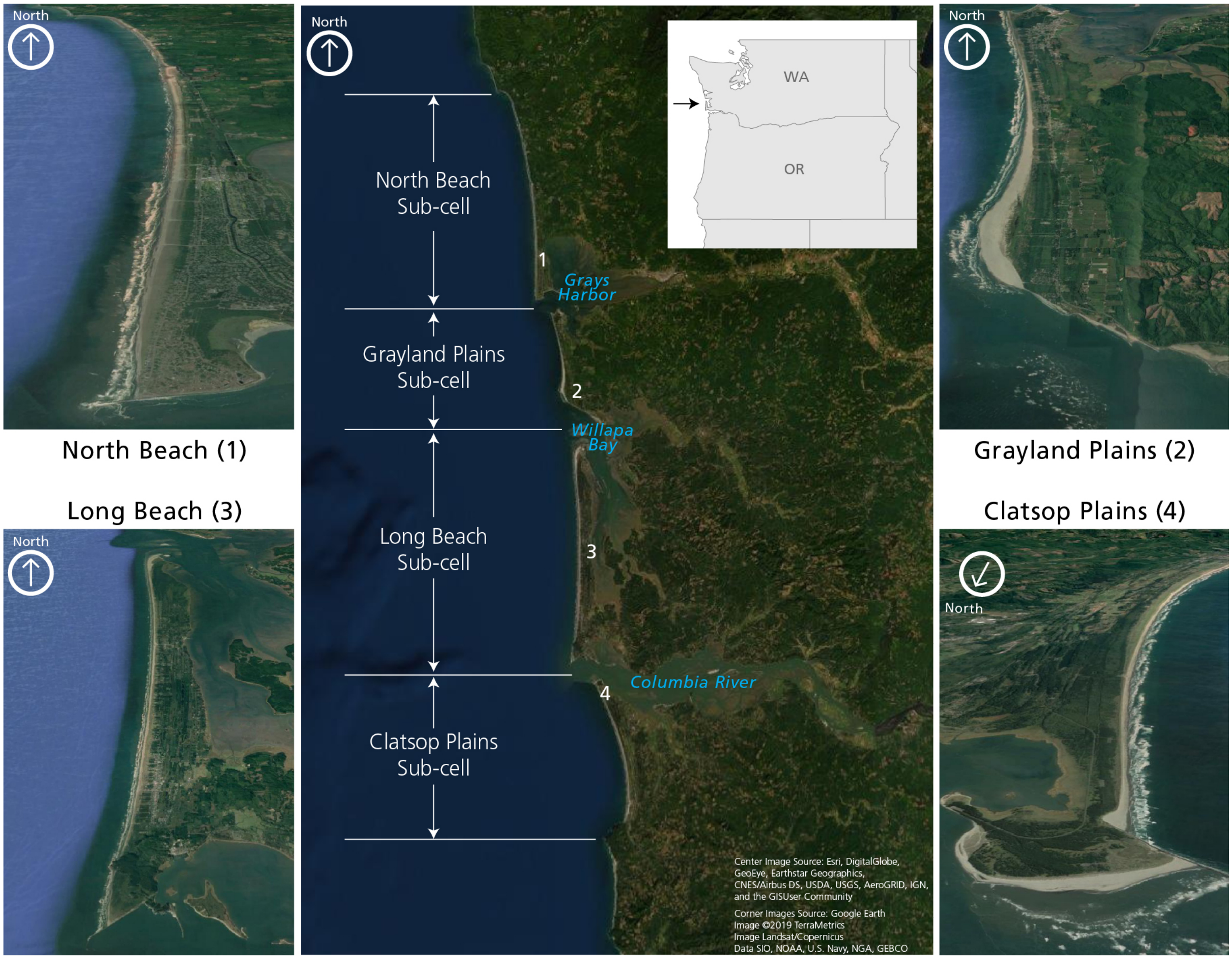


Figure 7. Map and photographs of the Columbia River littoral cell, with sub-cells identified. The Columbia River littoral cell extends ~165 km (~100 mi) along the Pacific Northwest coast of northwest Oregon and southwestern Washington. The sub-cells distribute sediment from the Columbia River. In the winter, winds from the southwest move sand north. In summer, winds from the northwest drive sand south. Because winter winds are stronger than summer winds, the dominant drift direction is north. Diagram modified by Rebecca Port (NPS) from Allan and Priest (2001), available at https://www.oregongeology.org/pubs/ofr/O-01-04.pdf (accessed 14 August 2019).

modify the coastal landscape. Large wave heights and acute wave angles during the strong El Niños of 1982–1983 and 1997–1998, for example, resulted in severe beach erosion and changes in shoreline orientation that persisted for several years (Allan et al. 2009).

Beginning around 1880, the US Army Corps of Engineers (USACE) installed north and south jetties at the MCR. In the 20th century, dams were constructed on the Columbia River and its tributaries. Jetties and dams have reduced the amount of sand available for natural beach maintenance in the Columbia River littoral cell and promoted both coastal erosion and accretion at different times of the year. Sand trapped in the lee areas of the jetties, such as behind the North Jetty at Cape Disappointment, contributes to beach accretion. For example, Mckenzie Rock, which forms a prominent feature on the beach, was once a sea stack surrounded by water. Since the end of the Pleistocene, sea level has been rising, moving the shoreline east. Without the North Jetty, the parking area and campground at Cape Disappointment would be under water. The beach north of the North Jetty grows seaward in summer and retreats in winter. Fencing has been installed to stabilize the sand (see Graham 2010).

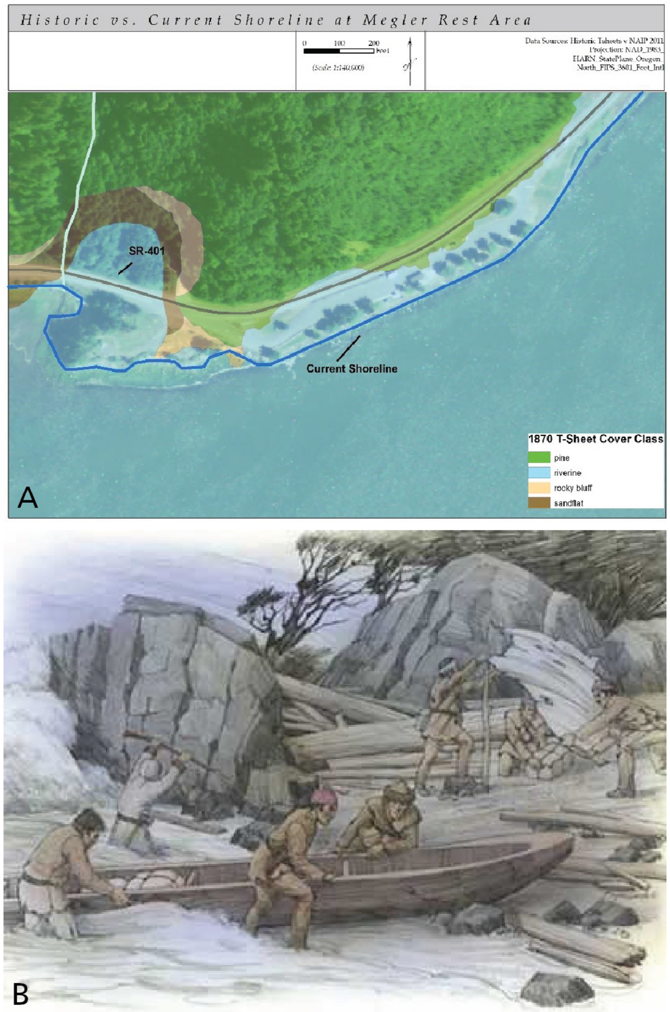


Figure 8. Map and illustration of Dismal Nitch. (A) A map comparing the current and historical shoreline at Dismal Nitch. The current shoreline is indicated by a dark blue line. The green areas were pine forests in the 1800s, while the tan area and brown area reflect 19th century rocky bluffs and sandflats, respectively. The black line traces the current location of state highway 401 (SH-401). Map courtesy of the NPS. (B) Artist Roger Cooke's rendition of the challenges, such as the fierce waves, strong winds, driftwood logs, and narrow rocky shoreline, faced by the Corps of Discovery at Dismal Nitch. The Sandstone at Megler (Tsm) that forms the cliffs surrounding Dismal Nitch blocked any escape by land. Drawing courtesy of the Washington State Historical Society, available at https://www.nps.gov/lewi/planyourvisit/dismal.htm (accessed 3 July 2017).

Cattle grazing on the Clatsop Plains destabilized the fragile soil of the native prairie. Combined with jetty development, there were roughly 1,200 ha (3,000 ac) of active sand dunes by 1930, which threatened farmlands and beach houses (Deur 2016). To stabilize beach dunes and slow the invasion of windblown sand into the grass prairies, the Soil Conservation Service (today's Natural Resources Conservation Service) planted Scotch broom (now considered an invasive plant), shore pine and non-native beach grasses. Beach progradation has continued regardless of the plantings, but the vegetation has prevented the open sand areas from expanding. The habitat of the dunes changed from an open diverse native prairie to dense monocultures of exotic grasses, Scotch broom shrublands and pine forests, thus affecting the natural ecosystem and sand transport along the coast. The transformation of dune environment to pine forest caused the local extirpation of a coastal butterfly (see Graham 2010).

Geologic Significance and Connections

The Corps of Discovery entered western Oregon and Washington in November during the rainy season. The average November precipitation for Astoria, for example, is 28.32 cm (11.15 in) (National Weather Service 2018). Even considering the increase in precipitation from global climate change (Lofgren and Huff 2013), rainfall in Astoria was abundant in 1805. In addition, precipitation does not typically fall in intense storms of short duration in the Pacific Northwest. Rather, precipitation generally falls as gentle, persistent rain that may last for days. Fog commonly creeps into low-lying areas and remains until midday. In early November, stormy weather, tides, waves, and wind pinned down the Corps of Discovery at what came to be called "Dismal Nitch" (fig. 8; DeVoto 1953; Ambrose 1996). Rain lasted 11 days. At high tide, waves crashed gigantic trees, some almost 61 m (200 ft) long and 2 m (7 ft) in diameter, into the camp. Their canoes were at the mercy of the waves and driftwood; their clothes and bedding were soaked. Overhanging rocks of basalt interbedded with basaltic sandstone and conglomerate (**Tsm**, **Tbr**, **Tbf**) prevented their escape by land. These rock units record submarine volcanic eruptions of lava that solidified into basalt and lithification of marine sediments deposited in intervals between eruptions, followed by accretion onto the coast as the oceanic plate continued to collide with the North American continent. At Dismal Nitch, the strata tilt to the northeast, suggesting that collision caused the rocks to be folded into a northwest–southeast trending anticline (convex fold). As deformation continued, the rocks were offset by northwest–southeast and northeast–southwest normal faults (fig. 4).

Desperate for a better campsite, the captains sent out Privates Colter, Willard, and Shannon on November 13, 1805, to explore the shoreline (Ambrose 1996). Around the point, they found a sandy beach of sediments

Figure 9. Photograph of Cape Disappointment and lighthouse in Cape Disappointment State Park, Washington.
Waves pound cliffs composed of Crescent Formation (Tc) basalt. Note the size of the driftwood logs washed up on the beach. Photograph by Adbar, utilized under the Creative Commons Attribution-Share Alike 4.0 International license (CC BY-SA 4.0, https://commons.wikimedia.org/wiki/File:Cape_Disappointment_and_Cape_Disappointment_Light.jpg (accessed 3 July 2017).

transported into the Columbia River estuary by rivers and streams and distributed along the coast by tides and waves (**Qf**). The rest of the explorers moved the next day to this location, now known as Middle Village–Station Camp. Inland from the beach, submarine basalt deposits (**Tbr**) similar to those at Dismal Nitch overlay middle Eocene submarine basalt flows of the Crescent Formation (**Tc**). These two units also dominate the landscape at Fort Columbia State Park. The axis of a northwest–southeast trending anticline bisects Middle Village–Station Camp and Fort Columbia State Park. Within a relatively small fault block on the southwestern limb of the fold, basalt breccia and flows (**Tbr**) interfinger with sandstone and siltstone of the Sandstone at Megler (**Tsm**).

From Middle Village–Station Camp, Lewis and Clark explored Cape Disappointment (fig. 9). Although they did not know it at the time, the cliffs at Cape Disappointment consist of 55.8 million–33.9 million-year-old (Eocene Epoch) Crescent Formation (**Tc**), the oldest rocks in the Cape Disappointment area of southwestern Washington (Wells 1989). The Crescent Formation forms the backbone of the north- to northwest-trending anticlinal uplifts in southwest Washington. The uplifts are asymmetric, with over-steepened west limbs dipping towards the ocean. Four complexly faulted and folded uplifts occur in the Cape Disappointment area (Wells 1989). Reverse faults bound the western margins of the uplifts. In addition to faulting, the Crescent Formation at Cape Disappointment and at Fort Columbia has rotated about 65° clockwise (Wells 1989). The Crescent Formation formed as a chain of seamounts (submarine volcanoes) in the Pacific Ocean basin. Active subduction compressed the seamounts against the western continental margin of North America. Features within the Crescent Formation document this submarine, volcanic terrain (see the Features and Processes chapter).

Figure 10. Photograph of the replica of the Salt Works in Seaside, Oregon.
The Corps of Discovery produced salt from ocean water. A fire in the oven-like compartment would heat saltwater and when fresh water evaporated, salt would be left in the kettles. The Oregon Historical Society re-established the long-forgotten salt-making site in 1900 based on the rockpile in Seaside and testimony of Jenny Michel, a Clatsop Indian born in 1816, who recalled her mother's memory of white men boiling water on that spot. NPS photograph by Jack E. Boucher, https://www.nps.gov/nr/twhp/wwwlps/lessons/108lewisclark/108visual3.htm (accessed 23 July 2018).

While they found abundant beach sand (**Qbs**) at Cape Disappointment, Lewis and Clark did not find any white men who were rumored to be living on the coast or a trading ship that might provide provisions for their return trip. On November 24, 1805, the captains consulted with the members of the party–including Sacagawea and York. Captain Clark recorded in his journal that they would explore the south side in search of a location for their winter camp. They hoped to find a location with enough game to support them throughout the winter, proximity to the ocean to produce salt, and a location conducive to contact with any trading ships (Moulton 1987).

At the end of November, the Corps of Discovery crossed over to the south side of the Columbia River. They camped near the present city of Astoria, Oregon, on younger, middle–early Miocene sedimentary rocks of the Astoria Formation (**Tac**), which were originally deposited in a submarine environment (Niem and Niem 1985). From the expedition's camp near the present town of Astoria, Oregon, Lewis explored Youngs Bay and the Netul River (now Lewis and Clark River) hoping to find a suitable winter campsite and the elk that the Clatsops said were plentiful in the region. Lewis canoed about 5 km (3 mi) from the mouth of the river, passing banks composed of unconsolidated floodplain deposits (**Qal**), until he found a suitable location on elevated ground near a spring, timber for a fort, plenty

Figure 11. Photograph of Tillamook Head viewed from the beach at Seaside, Oregon.
The cliff consists of the Smuggler Cove Formation (Tsc) at the base overlain by intrusive basalt of the Grande Ronde Basalt (Tgri) interlayered with the Cannon Beach Member of the Astoria Formation (Tac). Note the relatively wide beach. In 1964, Tillamook Head deflected a tsunami that swept across the beach and inundated Seaside, Oregon. Captain Clark traversed Tillamook Head on his way to Cannon Beach where he found a beached whale. A sea stack has been isolated from the mainland by wave erosion (far right in photo). Photograph by M. O. Stevens, with Creative Commons Attribution-Share Alike 1.0 Generic license (CC BY-SA 1.0), https://commons.wikimedia.org/wiki/File:Tillamook_Head_from_Seaside_-_Oregon.JPG (accessed 3 July 2017).

of elk, and a short distance from the ocean where they could obtain salt (Ambrose 1996).

The upper Eocene mudstones and siltstones of the Smuggler Cove Formation (**Tsc;** table 2), upon which Fort Clatsop was built, are also submarine deposits that were compressed and accreted onto the Pacific Northwest margin. The Smuggler Cove Formation forms higher ground relative to the adjacent geologic units because the tuffaceous siltstone, sandy siltstone, and glauconitic sandstone of the unit are more resistant to erosion than the unconsolidated river terrace (**Qt**), dune sand (**Qds**), and alluvial (**Qal**) deposits.

While the Corps of Discovery constructed Fort Clatsop and hunted, Alex Willard and Peter Wiser set out in the direction of what is now the Fort to Sea Trail (fig. 1) to find a route to the ocean and a location for a salt-making camp (Moulton 1987; Ambrose 1996). The trail traversed sand dunes (**Qds**) and beach sand (**Qbs**), ending at what is now Sunset Beach State Recreation Area. South of Sunset Beach, the expedition established the salt works on the shore of a cove north of Tillamook Head, in a location that is now part of the town of Seaside, Oregon. To obtain salt, sea water was boiled day and night in five large kettles, the fire fueled by trees and driftwood (fig. 10). By February 21, 1806, when the Corps of Discovery abandoned Fort Clatsop, the expedition had accumulated enough salt for the trip home.

On January 3rd, 1806, a group of Clatsop Indians visited the Corps of Discovery with items to trade. Among the items was whale blubber that they had obtained from their neighbors to the south, the Killamucks, who had found a whale on the beach. According to the Lewis and Clark journals, the blubber tasted like pork, only coarser and spongier, and when cooked, the blubber proved to be tender and palatable. Tired of eating dog, the men were ready to try more of the fat, so Clark put together a party of twelve to find the whale and bring some of the blubber back to camp. The Captains agreed to include Sacagawea, who had argued that because she had traveled so far with the Corps of Discovery and had not yet seen the coast, she should be permitted to be part of the group (Moulton 1987). Their route took them over Tillamook Head, which is now Ecola State Park, and across the same volcanic units that they had encountered in the Columbia River Gorge (fig. 11; Niem and Niem 1985; Niem and Horning 2006; Wells et al. 2009). Like the topography at Fort Clatsop, the headland is an example of inverted topography where basalt, originally deposited on the seafloor is now topographically higher than the surrounding area. The 200 m (660 ft) thick Grande Ronde intrusive basalt (**Tgri**) is much more resistant to erosion than the surrounding deposits of beach sand and alluvium. The basaltic lava originally invaded the submarine deposits of the Cannon Beach Member of the Astoria Formation (**Tac**). When the units were uplifted and exposed to erosion, the softer surrounding sediments were easily eroded, leaving the dense, interbedded basalt and sandstone as the present headland.

From the Astoria Column, visitors have excellent views of the various flows of the Columbia River Basalt Group that form inverted topography throughout northwestern Oregon. Built in 1926 to commemorate Astoria's role in the Astor family business history, the 38 m (125 ft)-tall, concrete and steel Astoria column contains an exterior spiral frieze with murals recording significant events in Oregon's early history, including the Lewis and Clark expedition (fig. 12). The Astoria Column towers from a basalt ridgeline that is 180 m (600 ft) above sea level and one of the few areas in the vicinity that is not a landslide deposit (see Graham 2010). The ridgeline consists of the baked contact between basalt and mudstone, and like Saddle Mountain and Tillamook Head, it is an example of invasive lava injected into mudstone and sandstone on the seafloor.

Figure 12. Photograph of the Astoria Column, Astoria Hill, Oregon.
Constructed in 1926, the concrete and steel Astoria Column was added to the National Register of Historic Places on May 2, 1974. The 38 m (125 ft)-tall column has a 164-step spiral staircase to an observation deck at the top of the column. Photograph by user MB298, utilized under the Creative Commons Attribution-Share Alike 4.0 International license (CC BY-SA 4.0), https://commons.wikimedia.org/wiki/File:Astoria_Column_from_base.jpg (accessed 23 July 2018).

Geologic Features, Processes, and Resource Management Issues

These geologic features and processes are significant to the landscape and history of Lewis and Clark National Historical Park. Some geologic features, processes, or human activities may require management for human safety, protection of infrastructure, and preservation of natural and cultural resources. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

During the 2009 scoping meeting (see Graham 2010), participants (see Appendix A) identified the following features, processes, and resource management issues. Each is discussed on tables 1 and 2 in the context of relevant geologic map units.

Geologic Features and Processes

The geologic features in Lewis and Clark NHP reflect recent coastal and fluvial processes, as well as tectonic processes associated with the Cascadia Subduction Zone that have been occurring for millions of years. In general, these features may be organized into the following general categories (table 3).

Eolian and Coastal Features

Eolian processes refer to wind-blown erosion, transportation, and deposition of sediments (Lancaster 2009). Features created by eolian processes include depositional landforms and deposits such as dunes, loess, and sand sheets, as well as erosional forms such as desert pavement, yardangs, and ventifacts. Sand dunes are the only eolian feature mapped in Lewis and Clark NHP. The NPS Geologic Resources Division Aeolian Resource Monitoring website, (http://go.nps.gov/geomonitoring) provides additional information.

Although coastline and shoreline are commonly used interchangeably, they refer to different areas along a coastal landscape. The shoreline marks the boundary between water and land and fluctuates because of tides and waves. The boundaries of the shore are marked by low tide and high tide. Coastal natural resources are in a transition zone between terrestrial and marine environments, and as such, include resources and characteristics of both types of environments (Bush and Young 2009). Coastal environments—shaped by waves, tides, wind, and geology—may include tidal flats, estuaries, river deltas, wetlands, dunes, beaches, barrier islands, bluffs, headlands, and rocky tidepools. The National Park Service manages 85 ocean, coastal, and Great Lakes parks with more than 18,000 km (11,200 mi) of shoreline. Several of the units in Lewis and Clark NHP border either the Pacific coast or the Columbia River estuary.

The coastline begins where the shore ends at its high tide mark (farthest landward), and the coast extends landward to the first major change in terrain features, which may be miles inland. Shoreline deposits defined on the source map by Wells (1989) as "**Qb**" are mapped on the GRI GIS data as beach sand (**Qbs**) within Cape Disappointment State Park. The source map by Niem and Niem (1985) identified beach sand (**Qbs**) within Sunset Beach State Recreation Area. Dunes sands (**Qds**) inland of **Qbs** deposits are above high tide; storm waves do not typically impact the inactive, vegetated portion of the dunes, but the lower part may be occasionally inundated. The headlands and cliffs are above high tide but mark the boundary between land and water. For this report, features associated with the Washington and Oregon coast, whether below high tide or not, are considered "coastal" features.

The following features are included in this category (table 3):

- Sand dunes
- Beach
- Sea caves (fig. 13)
- Sea stacks
- Headlands, cliffs
- Clatsop Spit
- Tide pools
- Jetties (fig. 14)

Fluvial (River) Features

Dismal Nitch, Middle Village–Station Camp, Fort Columbia, and parts of Cape Disappointment and Fort Stevens border the mouth of the Columbia River (MCR). Fort Clatsop and Netul Landing border the Lewis and Clark River.

Fluvial features include (table 3):

- Floodplain and natural levees
- River terraces

Figure 13. Photograph of a sea cave exposed during low tide at Cape Disappointment.
The cave has formed along a vertical fracture in the bedrock. The cave is approximately 10 m (30 ft) tall (Chris Clatterbuck, Chief of Resources, Lewis and Clark NHP, written communication, 1 July 2019). June 2007 photograph by user loggedout, Creative Commons Attribution-Share Alike 3.0 Unported License (CC BY-SA 3.0), https://commons.wikimedia.org/w/index.php?curid=39346949 (accessed 26 July 2017).

Submarine Features

When a major offshore earthquake occurs, the disturbance causes mud and sand on the continental slope to cascade into submarine canyons where the density currents transport the sediments down-slope to the abyssal plain. The density currents and subsequent deposits are called turbidites (fig. 15). The coarser sediments that form the base of a turbidite are clearly distinct from the mud and fine particulate matter that slowly settles out of the water column. Turbidites that occurred in the past accreted to the continental margin as a result of tectonic processes and are now exposed in several formations in the park (table 3).

Other submarine features that are now exposed in park units include invasive basalt and submarine basalt (**Tgri**, **Tbr**, **Tbf**, **Tc**). "Invasive" basalt defines lava that flowed through the Columbia River valley to the ocean and burrowed into seafloor sediment. Basalt that flowed from submarine volcanic vents cooled rapidly to form pillow-shaped features.

Submarine features now exposed in the park include (table 3):

- Turbidites
- Invasive basalt
- Submarine basalt

Landslides

Landslides in the Pacific Northwest form primarily from excessive rainfall on steep slopes and from earthquakes associated with the CSZ. Jumbled strata and chaotic bedding resulting from old landslides is present in the Astoria Formation (**Tac**) and the Crescent Formation (**Tc**) (table 3).

Tectonic Features

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

A fault is a fracture in rock along which rocks have moved. The three primary types of faults are normal faults, reverse faults, and strike-slip faults (fig. 4). Faults are classified based on the relative motion of rocks on either side of the fault plane as described in fig. 4. Thrust faults are reverse faults with a low angle (<45°) fault plane. Décollements, or detachment faults, are very low angle (nearly horizontal) reverse faults with large displacement (kilometers to tens of kilometers).

The GRI GIS data for Lewis and Clark National Historical Fault identify the northwest–southeast-trending anticline at Middle Village–Station Camp and Fort Columbia State Park, as well as numerous normal and reverse faults, some of which are named (table 3).

Tectonic forces have also accreted volcanic rocks that were once deposited in submarine valleys to the mainland, and these rocks, being more resistant to erosion than the surrounding sedimentary rocks, now form highlands. This stratigraphy wherein

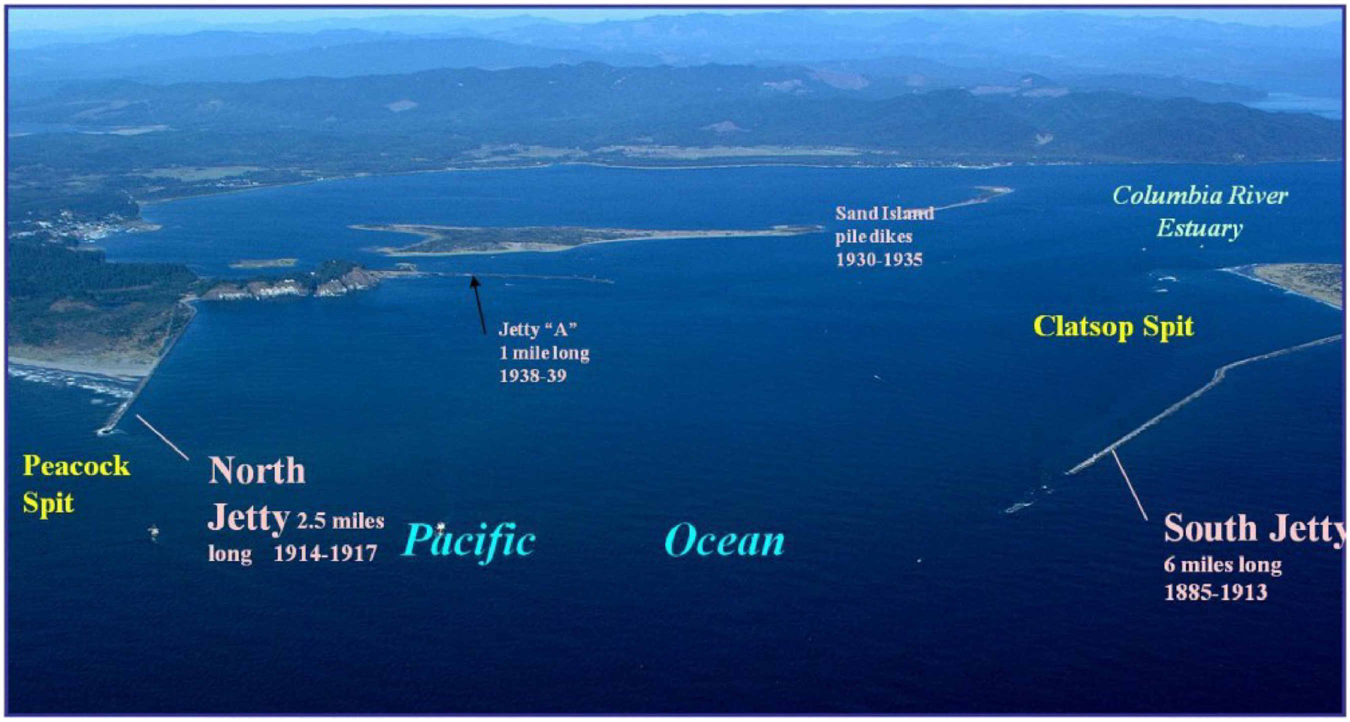


Figure 14. Annotated photograph showing the jetties at the mouth of the Columbia River. The jetties are operated and maintained by the US Army Corps of Engineers. The 4.0 km (2.5 mi) long North Jetty was built from 1913 to 1917. The 11 km (6.6 mi) long South Jetty, on the Oregon side, was built from 1885 to 1895. Jetty "A", 0.5 km (0.3 mi) long, was built in 1939. The navigation channel serves as the border between Washington and Oregon. US Army Corps of Engineers image available at http://usaceportland.armylive.dodlive.mil/index.php/2014/08/mcr-north-jetty-access-restricted-beginning-fall-2014/ (accessed 24 July 2018).

rocks deposited in relatively low areas now form topographically high regions is called "inverted topography."

Tectonic features found in Lewis and Clark NHP include (table 3):

- Folds
- Normal faults
- Reverse/thrust faults
- Inverted topography

Fossils

Fossils listed in table 3 are from Fay et al. (2009). Although few fossils have been found within the units of Lewis and Clark NHP, many fossils have been discovered in the same geologic units outside the boundaries of the park. Refer to Fay et al. (2009) for a list of these fossils. Fossils help to interpret past depositional environments and paleoclimate, as well as the age of the deposits.

Paleontological features in the park fall into the following two categories (table 3):

- Fossils
- Ichnofossils (trace fossils)

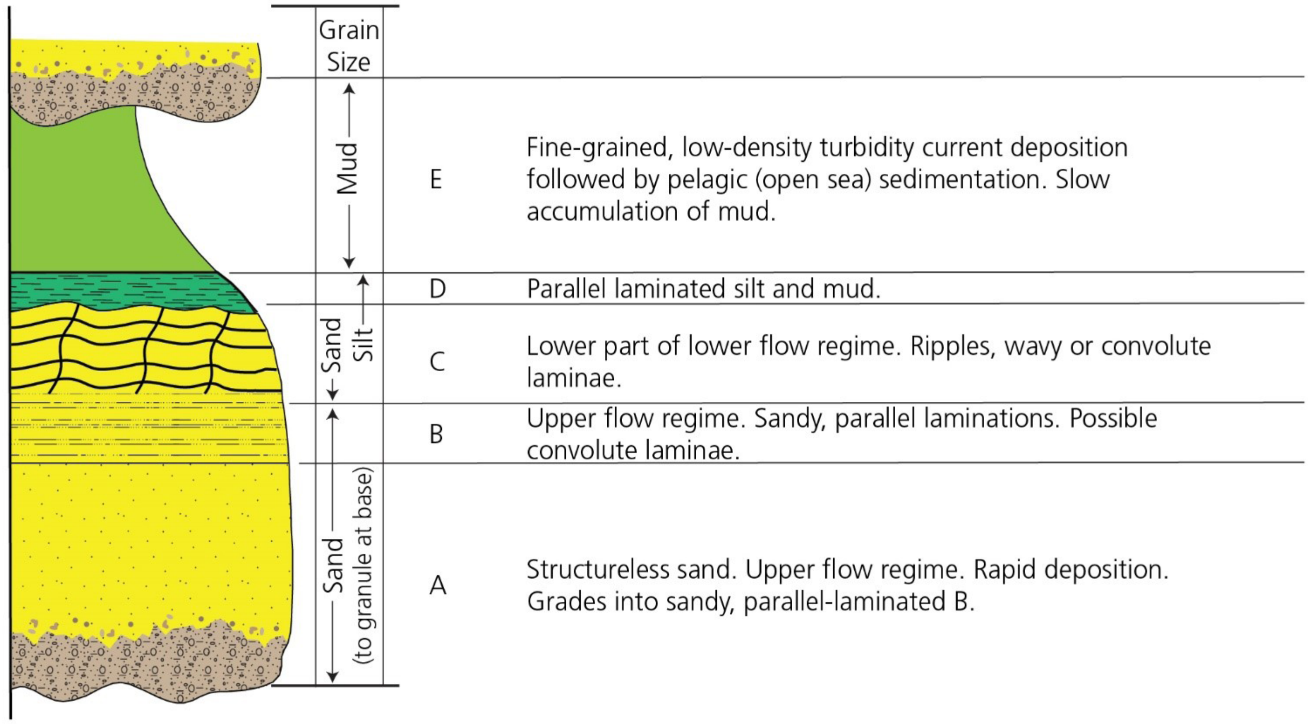


Figure 15. Turbidite diagram.
Density currents are arranged in a series of layers called a Bouma Sequence, after A. H. Bouma (1962). A Bouma sequence consists of fining-upward layers (A–E) that reflect settling in a marine setting. The lack of intermixing indicates that deposition occurred below storm wave base, at least 250–300 m (820–980 ft) deep (Walker 1992). The base of each sequence tends to be sharp and flat, with no indication of seafloor erosion, and contains abundant markings, such as those left by sticks, stones, or other rigid objects (tool marks), fluid scour of underlying mud (scour marks), or trails or burrows (organic marks) made by organisms and filled in by the turbidity current. Diagram modified from SEPM Strata, http://www.sepmstrata.org/page.aspx?pageid=37 (accessed 9 July 2017).

Table 3. Features and processes associated with geologic units in Lewis and Clark NHP.

* Fossils in the geologic units are known from within Lewis and Clark NHP and from the surrounding area. See Fay et al (2009).

Feature Group	Feature Name	Process	Geologic Map Unit (map symbol)	Feature and Process Characteristics
Eolian and Coastal Features	Sand dunes	On-shore winds move loose sand grains	Dune sand (**Qds**)	North–south beach ridges with well sorted, cross-bedded quartz and feldspar sand grains. Heavy minerals (e.g. magnetite and ilmenite) have formed laminae.
	Beach (fig. 11)	Waves, tides, storms, longshore current	Beach sand (**Qbs**)	Moderately well-sorted quartz and feldspar sand with thin, dark layers of heavy minerals.
	Sea caves (fig. 13)	Waves erode fractured zones	Crescent Formation (**Tc**) Grande Ronde Basalt (**Tgri**)	Several caves have developed in the Cape Disappointment and Ecola park units (fig. 13).
	Sea stacks (fig. 11)	Wave erosion isolates pillars of rock from the mainland	Crescent Formation (**Tc**) Grande Ronde Basalt (**Tgri**)	Sea stacks occur offshore at Ecola State Park. Once a sea stack, McKenzie Rock in Cape Disappointment is now surrounded by sand.
	Headlands, cliffs (fig. 9, 12)	Subduction, accretion, and wave erosion	Grande Ronde Basalt (**Tgri**) Astoria Formation (**Tac**, **Tac1**) Crescent Formation (**Tc**)	Inverted topography in which basalt deposited on the ocean floor now forms topographic highlands occurs in the Cape Disappointment and Ecola park units.
	Clatsop Spit	Reworked river sediment by wind, waves, and sea level	Beach sand (**Qbs**)	A spit formed at the MCR as sea level rose following the Pleistocene ice ages. Heavy mineral deposits may be a few meters thick.
	Tide pools	Tides	Astoria Formation (**Tac1**) Grande Ronde Basalt (**Tgri**) Smuggler Cove Formation (**Tsc**) Crescent Formation (**Tc**)	Tides fill depressions in exposed bedrock. Pools contain marine organisms (e.g. echinoids, star fish).
	Jetties (fig. 14)	Development	Linear features	Jetties border the MCR between Cape Disappointment in Washington and Fort Stevens in Oregon. The jetties impact the sand supply along the coast and in the navigation channel.
Fluvial Features	Floodplain and natural levees	Overbank deposits from floods	Fluvial/estuarine deposits (**Qf**) Alluvium (**Qal**)	Unconsolidated clay, silt, sand, and gravel along rivers and streams. Dikes currently limit flooding.
	River terraces	Channel incision	Terrace deposits (**Qt**)	Elevated alluvial deposits at Fort Clatsop resulted from the entrenchment of the Lewis and Clark River.

Table 3 (continued). Features and processes associated with geologic units in Lewis and Clark NHP.

Feature Group	Feature Name	Process	Geologic Map Unit (map symbol)	Feature and Process Characteristics
Submarine Features	Turbidites	Density (turbidity) currents below ocean storm wave base	Astoria Formation (**Tac**, **Tac1**) Sandstone at Megler (**Tsm**) Smuggler Cove Formation (**Tsc**) Lincoln Creek Formation (**Tlc**) Siltstone at Shoalwater Bay (**Tsb**)	**Tac**, **Tac1**. BC and CD intervals in a Bouma Sequence (see fig. 15). Cross-lamination, basal markings, convolute bedding. **Tsm**. Graded bedding, planar laminations, cross-laminated, interbedded siltstone, basal markings. **Tsc**. Abundant ***Helmenthoida*** burrows, which indicate bathyal to abyssal depths of ~2,000 m (~6,500 ft) and are associated with turbidites (Pemberton et al. 1992). Glauconitic sandstone (the green mineral glauconite forms only in marine settings). Deep water foraminiferal assemblages (Fay et al. 2009). **Tlc**. Parallel laminations, glauconitic sandstone, large-scale soft-sediment deformation, burrows. **Tsb**. Laminated, thin-bedded siltstone may be Bouma interval D (see fig. 15).
	Invasive basalt	Lava that flowed into the ocean and burrowed into seafloor sediment	Grande Ronde Basalt (**Tgri**)	Intrudes upper Eocene to middle Miocene sedimentary rock units. Invades Astoria Formation (**Tac**, **Tac1**) in Ecola State Park.
	Submarine basalt	Lapilli ejected from submarine volcanoes	Basalt lapilli breccia and flows at Fort Columbia (**Tbr**, **Tbf**)	Pillow-shaped basalt. Interbedded with **Tsm**. Volcanic glass altered to green smectite clays.
	Submarine basalt	Extrusion of lava on the seafloor from fissures and vents	Crescent Formation (**Tc**)	Pillowed basalt. Volcanic glass altered to green smectite clays. Clay minerals, zeolite, calcite, and quartz-filled vesicles and fractures.
Landslide Features	Landslides	Excessive rainfall and earthquakes from subduction lead to slope failure	Landslides occur in the Astoria Formation (**Tac**, **Tac1**) and in the Crescent Formation (**Tc**).	**Tac**, **Tac1**. Jumbled strata. Contorted bedding. Many landslides and slumps in Ecola State Park and surrounding Fort Clatsop Visitor Center. Older slumps lack trees. **Tc**. Landslides have occurred near the lighthouses at Cape Disappointment.

Table 3 (continued). Features and processes associated with geologic units in Lewis and Clark NHP.

Feature Group	Feature Name	Process	Geologic Map Unit (map symbol)	Feature and Process Characteristics
Tectonic Features	Folds	Subduction of tectonic plates	Crescent Formation (**Tc**)	Forms crest of NW—SE anticline at Middle Village–Station Camp and Fort Columbia.
Tectonic Features	Normal faults	Subduction of the Juan de Fuca plate beneath the North American plate	Lincoln Creek Formation (**Tlc**) Siltstone at Shoalwater Bay (**Tsb**) Crescent Formation (**Tc**) Basalt breccia and flows (**Tbr**, **Tbf**) Sandstone at Megler (**Tsm**)	Normal, near-vertical faults define the borders of horsts (upthrown blocks) and grabens (downthrown blocks) in the Astoria Basin (see the cross-sections in the GRI GIS data; lewi_geology.mxd).
Tectonic Features	Normal faults	Subduction of the Juan de Fuca plate beneath the North American plate	Smuggler Cove Formation (**Tsc**) Grande Ronde Basalt (**Tgri**)	Normal faults form the contact between these formations at Ecola State Park (see GRI GIS data).
Tectonic Features	Reverse/ thrust faults	Subduction of the Juan de Fuca plate beneath the North American plate	Lincoln Creek Formation (**Tlc**) Crescent Formation (**Tc**)	Chinook Fault juxtaposes **Tlc** and **Tc** and forms the eastern border of the Shoalwater Syncline, northwest of Fort Columbia State Park; the Naselle-Nemah thrust fault separates the Nemah Syncline to the west from the Radar Ridge Syncline (see GRI GIS data).
Tectonic Features	Inverted topography	Differential erosion. Lava is more erosion resistant than surrounding strata.	Smuggler Cove Formation (**Tsc**) Astoria Formation (**Tac**) Grande Ronde Basalt (**Tgri**) Crescent Formation (**Tc**)	Deposited in submarine environments, these rocks were accreted to the mainland and have reversed their elevation, forming topographically high areas as erosion removed the less resistant rocks and sediment.
Fossils*	Body fossils	Fossilization	Astoria Formation (**Tac**) Smuggler Cove Formation (**Tsc**) Lincoln Creek Formation (**Tlc**) Siltstone at Shoalwater Bay (**Tsb**) Sandstone at Megler (**Tsm**) Crescent Formation (**Tc**)	**Tac**. Mollusks, foraminifera, nautiloids, marine mammals (whales, sea lions, eared seals, porpoise), shark teeth, fish vertebrae, turtle, chalicothere similar to Moropus, rhinoceros tooth, an estuarine herbivorous mammal, and fossil plants. **Tsc**. Bivalves, gastropods, foraminifera. **Tlc**. Barnacles, vertebrates (whales, albatross, fish), decapods, aturiid nautiloids, sponges. **Tsb**. Foraminifera, mollusks, crabs. **Tsm**. Foraminifera. **Tc**. Bivalves, brachiopods, nautiloid fragments, solitary and colonial corals, echinoids, crab, radiolarian, coccolithophores, foraminifera, polychaete worm tubes, scaphopods, a barnacle, two sharks, and fish otoliths.
Fossils*	Ichnofossils (trace fossils)	Trails, tracks, and burrows made by biologic organisms	Smuggler Cove Formation (**Tsc**) Lincoln Creek Formation (**Tlc**)	**Tsc**. Abundant grazing trails of ***Helmenthoida*** (marine worms). Also, grazing trails of ***Scalarituba*** (worms, snails, or arthropods) and feeding traces of marine worms ***Zoophycos***, ***Taenidium annulate***, ***Teichichnus***, ***Planolites***, and ***Chondrites***. **Tlc**. Narrow, U-shaped *Tisoa* burrows

Geologic Resource Management Issues

Because the units of Lewis and Clark NHP include beaches, headlands, the Columbia River estuary, and upland terrain, the geologic resource management issues are diverse and complex. Issues associated with the park may be categorized as follows (table 4):

Hazards Associated with the Cascadia Subduction Zone

- Earthquakes (seismic activity)
- Tsunamis
- Liquefaction
- Volcanic activity

Landslide Hazards

Flooding

Paleontological Inventory

Cave Inventory

Issues Associated with Global Climate Change

- Water resources
- Sea level rise
- Inland and coastal flooding
- Coastal erosion
- Precipitation and mass wasting

Issues and Projects Associated with Human Activity

- Jetties
- Shoreline stabilization along the Columbia River
- Dredging
- Beach nourishment
- Hydrocarbon exploration

Hazards Associated with the Cascadia Subduction Zone

CSZ hazards are interrelated. Seismic activity (earthquakes) may generate tsunamis and turbidites in the submarine environment and liquefaction of unconsolidated sediments along the coast and MCR. However, earthquake magnitudes vary, and earthquakes may occur at different subsurface levels causing various amounts of shaking and subsequent surface damage. Ground shaking may also trigger landslides, but landslides may also be triggered by other natural processes such as intense rainfall, waves undercutting cliffs, or bank erosion caused by increased runoff. Subduction may also generate volcanic activity.

Real-time earthquake data may be acquired on Pacific Northwest Seismic Network (PNSN) website (https://pnsn.org/) with additional information on the PNSN Earthquake Sources website; http://www.pnsn.org/outreach/earthquakesources) and the USGS Earthquake Hazards Program website (https://www.usgs.gov/natural-hazards/earthquake-hazards).

The Oregon DOGAMI maintains the Statewide Geohazards Viewer ("HazVu"; http://www.oregongeology.org/hazvu/) map viewer that provides a way to view many different geohazards in Oregon. A PDF of the HazVu legend is also available online to accompany the map (http://www.oregongeology.org/hazvu/hazvu-legend-descr_jan2018.pdf). The Oregon Office of Emergency Management also maintains a website with information about the CSZ (http://www.oregon.gov/oem/hazardsprep/Pages/Cascadia-Subduction-Zone.aspx).

The State of Washington Geologic Information Portal (https://geologyportal.dnr.wa.gov/) and Geologic Hazard Maps (https://www.dnr.wa.gov/programs-and-services/geology/geologic-hazards/geologic-hazard-maps) are interactive map viewers displaying multiple hazards, as well as evacuation routes.

Earthquakes

Earthquakes can trigger coastal area subsidence, landslides, tsunamis, and almost instantaneous liquefaction of fine-grained, unconsolidated sediment (table 4). Landslides, such as those underlie Ecola State Park, may be reactivated by seismic activity. Earthquakes occur in Oregon and Washington from three different source areas (fig. 3): (1) crustal earthquakes occur along relatively shallow faults within 16 km (10 mi) of the surface, (2) intraplate earthquakes occur about 32–64 km (20–40 mi) below the surface, and (3) great offshore earthquakes occur along a major fault that parallels the Oregon–Washington coast (Madin and Mabey 1996). Most of the potentially active faults affecting Washington and Oregon are mapped between the CSZ and the coast.

Crustal earthquakes are the most common, and the faults generating these earthquakes may be visible at the surface. Rarely are earthquake magnitudes greater than 6. The 1993 earthquakes that shook the Puget Sound and Klamath Falls areas, for example, registered magnitudes of 5.6–6. However, the historic record is too short to accurately represent the threat from crustal earthquakes, and geoscientists believe that shallow faults in Oregon and Washington can generate earthquake magnitudes of 6.5–7 (Madin and Mabey 1996).

In 1949 and 1965, the Puget Sound area was severely shaken by intraplate earthquakes. Intraplate earthquakes occur within the Wadati–Benioff zone where remnants of the ocean floor continue to be

Figure 16. Photographic evidence of the 1700 CE tsunami that struck the Pacific Northwest. (A) Geologist Brian Atwater examines organic remains buried under sediment from the 1700 CE tsunami on the Lewis and Clark River. (B) Dark organic matter buried by the 1700 CE tsunami and marks the boundary between pre- and post-tsunami deposits. Photographs courtesy of the NPS.

subducted beneath the North American continent (fig. 3). Intraplate earthquakes may generate magnitudes of 7–7.5 and may occur anywhere under the Coast Range or western Willamette Valley (Madin and Mabey 1996).

Subduction zone earthquakes (fig. 3) typically generate earthquakes with the greatest magnitudes. Magnitude 8–9 earthquakes occur at these zones where pieces of the crust are being shoved deep into the Earth beneath less-dense crust. A 13-year study of the CSZ, completed in 2012 by Oregon State University researchers documented at least 19 CSZ earthquakes with magnitudes of 8.7–9.2 that have occurred over the last 100,000 years (fig. 3; Goldfinger et al. 2012). The study also documented a recurrence interval of ~500–530 years for large earthquakes of magnitude 8.5–9.2 along the northern segment of the CSZ from Newport, Oregon, to Vancouver Island (Goldfinger et al. 2012). However, the recurrence interval for major earthquakes is much shorter along the southern segment of the CSZ where major earthquakes occur approximately every 240 years (Goldfinger et al. 2012). The southern section also experienced 22 additional earthquakes that did not impact the northern end of the fault. Because of written records in Japan that document how a tsunami destroyed that year's rice crop that was stored in warehouses and field work by geologist Brian Atwater along the Lewis and Clark River, researchers know that the last major CSZ earthquake to strike the Pacific Northwest occurred on January 26, 1700 (fig. 16; Atwater et al. 2005). According to the study by Oregon State, during the next approximately 50 years, there is a 40% chance of a major earthquake in the Coos Bay, Oregon, region that could approach the 9.0–9.1 magnitude Tohoku earthquake that devastated Japan in March, 2011 (Goldfinger et al. 2012). The US Geological Survey estimates that there is a 25%–40% chance of an earthquake with a magnitude greater than 5.5 occurring in the Lewis and Clark NHP area within the next 100 years (fig. 17).

The earthquake hazard maps edited by Madin and Mabey (1996) show all the faults in Oregon that are known or suspected of generating earthquakes. The faults were divided into three categories based on their most recent activity: (1) Holocene or late Pleistocene faults that were active within the last approximately 20,000 years, (2) late Quaternary faults active from 20,000 to 780,000 years ago, and (3) Quaternary faults active within the last 1,600,000 years. Faults mapped between the CSZ fault and the coastline are primarily Holocene or late Pleistocene faults. Although faults are mapped on the GRI GIS data, Madin and Mabey (1996) did not map any earthquake-generating faults in Clatsop County, where the Oregon units of Lewis and Clark National Historic Site are located. However, as Madin and Mabey point out, significant faults may not break the surface, as was the case with the 1993 earthquakes that shook the Puget Sound and Klamath Falls areas, or surface expression of the faults may be obscured by weathering, erosion, or vegetation. Consequently, they caution about using the maps to identify the presence or absence of faults in specific areas. The presence of faults does not indicate the presence of a hazard nor does the absence of faults indicate the absence of a hazard (Madin and Mabey 1996).

Should a magnitude 9.0 CSZ earthquake occur, the DOGAMI HazVu map predicts severe shaking will impact Fort Stevens State Park, Sunset Beach Recreation Area, Seaside, a thin strip of coast at Ecola State Park, and Fort Clatsop.. Very strong to severe shaking will be felt throughout most of Ecola State Park and the uplands surrounding Astoria.

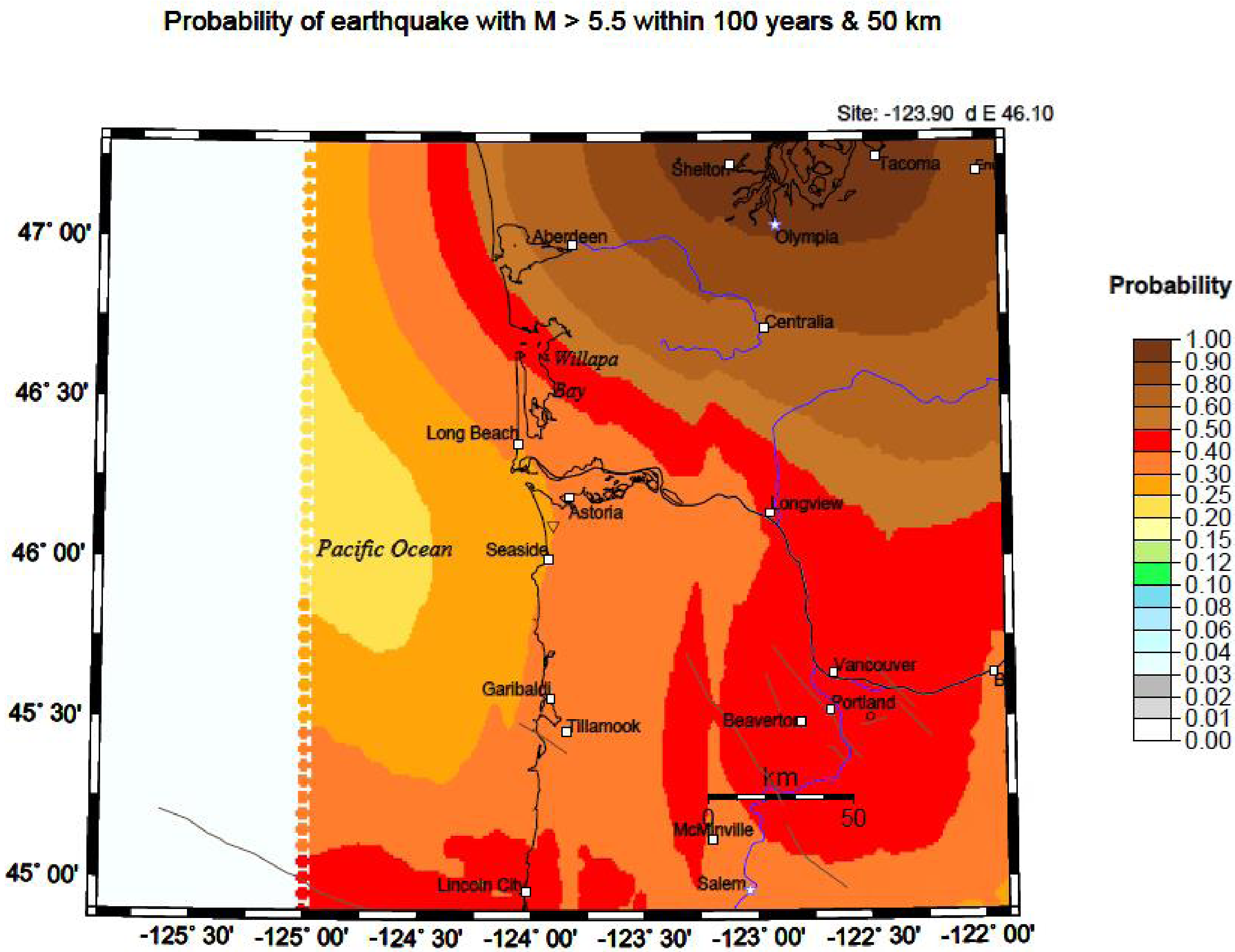


Figure 17. Earthquake probability map.
The probability of an earthquake occurring within the next 100 years with a magnitude greater than 5.5 is between 0.25 (25% chance) and 0.30 (30% chance) for Cape Disappointment, Fort Stevens State Park, Sunset Beach State Recreation Area, the Salt Works at Seaside, and Ecola State Park. The probability of an earthquake occurring within the next 100 years with a magnitude greater than 5.5 is between 0.30 (30% chance) and 0.40 (40% chance) for Fort Columbia State Park, Middle Village–Station Camp, Dismal Nitch, Fort Clatsop, and Netul Landing. Map courtesy of the US Geological Survey.

Because of the CSZ, Washington ranks second behind California for the potential for large, damaging earthquakes according to the Washington Department of Natural Resources. Their website includes a seismic risk map of potentially active faults and of potential damage resulting from seismic shaking (https://www.dnr.wa.gov/programs-and-services/geology/geologic-hazards/earthquakes-and-faults). Not surprisingly, Washington's west coast and MCR that includes the park units have a high potential for damage due to earthquake shaking.

Turbidites (fig. 15) have been useful in documenting the earthquake history of the CSZ. By using carbon-14 analysis to date the fine particles, researchers were able to provide reasonable ages for major earthquakes in Oregon over the past 10,000 years (Goldfinger et al. 2012). Earthquake history beyond 10,000 years is difficult to reconstruct because sea level was much lower and West Coast rivers deposited sediments directly into offshore canyons, confusing the distinction between storm debris and earthquake-generated turbidites. According to Goldfinger et al. (2012), the turbidite data is correlative with the tsunami record that goes back about 3,500 years. A detailed study of turbidites deposited on the continental shelf found that smaller events of limited extent occurred at intervals of 410–500, 300–380, and 220–240 years (Goldfinger et al. 2012).

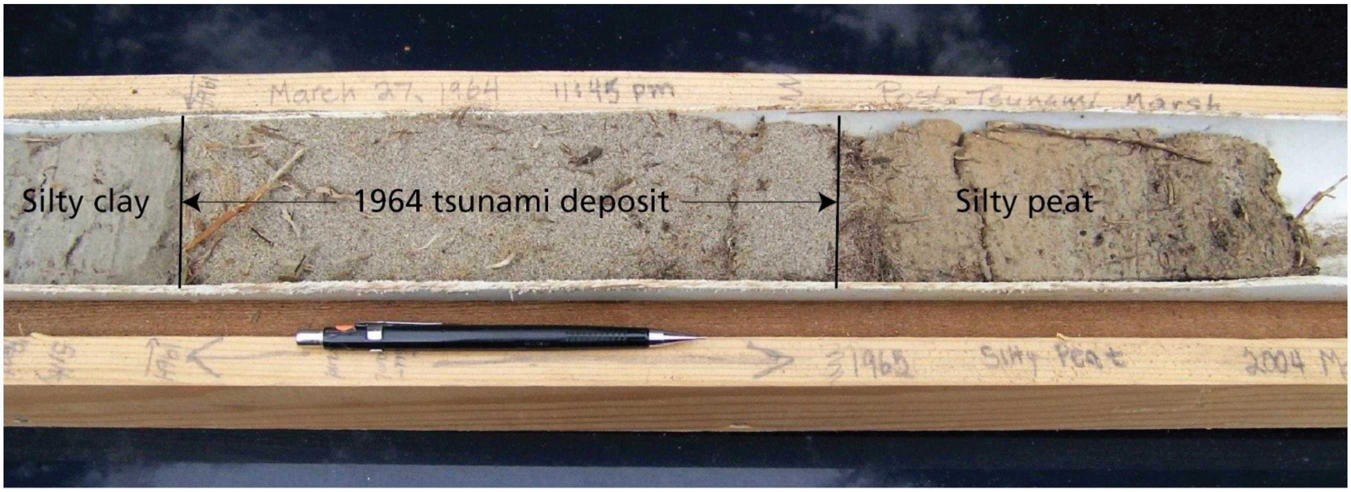


Figure 18. Photograph of a Tsunami deposit core, Seaside, Oregon.
Core through sandy sediments deposited by the 1964 tsunami in Seaside, Oregon, that resulted from the Great Alaska earthquake. Silty peat overlies the tsunami deposit, which sharply overlies gray, silty clay. The top of the core is to the right. The pencil is 14 cm (5.5 in) long. Photograph courtesy of Tom Horning (Horning Geosciences) with annotations by the author.

In the *Geological Monitoring* chapter about earthquakes and seismic activity, Braile (2009) described the following methods and vital signs for understanding earthquakes and monitoring seismic activity: (1) monitoring earthquakes, (2) analysis and statistics of earthquake activity, (3) analysis of historical and prehistoric earthquake activity, (4) earthquake risk estimation, (5) geodetic monitoring and ground deformation, and (6) geomorphic and geologic indications of active tectonics.

Tsunamis

Tsunamis generated by local or distant submarine earthquakes may impact the Pacific Northwest coast. In 1964, for example, the magnitude 9.2 Great Alaska Earthquake generated a tsunami that inundated Seaside, Oregon, where the Salt Works unit is located (fig. 18). The Great Alaska Earthquake was the largest recorded earthquake in US history and the second largest recorded by modern instruments (Brocher et al. 2014; Haeussler et al. 2014). The tsunami caused damage as far away as Hawaii and Japan and disrupted rivers, lakes, and waterways in Texas and Louisiana. At Cape Disappointment, the highest wave from the tsunami was 2.5 m (8.3 ft) above mean sea level (Walsh et al. 2000). The peninsula was flooded, but no damage occurred to the Coast Guard station. Tsunami evacuation maps for Oregon and Washington are available at the website for the Northwest Association of Networked Ocean Observing Systems (NANOOS; http://nvs.nanoos.org/TsunamiEvac). Those maps distinguish between zones impacted by local and distant tsunamis. Local tsunamis are those produced from the CSZ and can come onshore within 15 to 20 minutes after the earthquake. A distant tsunami, on the other hand, may take 4 hours or more to reach land.

Along the Washington coast, a magnitude 9 earthquake along the CSZ with a maximum slip of 27 m (89 ft) is expected to trigger a tsunami that will inundate Cape Disappointment to a maximum depth of 3–9 m (10–30 ft). The first wave is expected to arrive at the outer coast in approximately15–20 minutes following the earthquake (Eungard et al. 2018, sheet 6). The tsunami may reach about 3 m (10 ft) maximum depth along the shoreline from Cape Disappointment to Chinook Point, which is within Fort Columbia State Park. The first wave should reach Chinook Point in approximately 30 minutes. The speed of the tsunami at Cape Disappointment may be over 9 knots, but this will diminish to less than 3 knots at Chinook Point (Eungard et al. 2018, sheet 4). Within minutes of the CSZ earthquake, the land surface will subside, causing local flooding of low-lying areas. Inundation is estimated to continue for 4–24 hours, which will inhibit search, rescue, and recovery efforts. Middle Village–Station Camp and Dismal Nitch are outside of the Eungard et al. (2018) study area; however, the visitor use areas at both sites are under 8 m (26 ft) in elevation, and the park advises staff and visitors to evacuate to higher ground in the event of a tsunami.

Both local and distant tsunamis will inundate park units along the Oregon coast, as well as Netul Landing on the Lewis and Clark River. Distant tsunamis will flood Clatsop Spit in Fort Stevens State Park and spread inland from Jetty Lagoon to the Jetty Road. Along Columbia Beach, the distant tsunami evacuation zone extends from 7.6 m (25 ft) to 7.9 m (26 ft) above mean sea level. The local tsunami evacuation zone includes all of Fort Stevens State Park except for limited high areas near Coffenbury Lake and adjacent to Ridge Road. The western segment of Fort to Sea Trail, which terminates at Sunset Beach State Recreation Area, will be flooded by tsunamis as well. The distant tsunami evacuation zone includes a narrow strip of Sunset Beach to 7.0 m (23 ft) above sea level. However, the local tsunami evacuation zone includes all the recreation area and all the Fort to Sea Trail to a maximum elevation of 11 m (36 ft), leaving older beach ridges that are oriented parallel to US Highway 101 as assembly areas. Evacuation zones and evacuation routes may be found on the Oregon Tsunami Clearinghouse website (https://www.oregongeology.org/tsuclearinghouse/pubs-evacbro.htm).

Seaside, Oregon, which includes the Salt Works, will be severely inundated by both distant and local tsunamis (see the Seaside & Gearhart map and brochure on the Oregon Tsunami Clearinghouse website). A distant tsunami will flood the area between the coast and an elevation of 4.6 m (15 ft), which includes most of Seaside, all the structures along the Necanicum River and Neawanna Creek, and the Seaside Municipal Airport. A local tsunami will swamp even more area, inundating the coastline to an elevation of 19–27 m (61–87 ft) and leaving only the Coast Range foothills as assembly areas. Tillamook Head may deflect tsunami waves and redirect them to the north where they may superimpose on other waves, creating mountains of water rather than simply a plateau of water coming ashore (see Graham 2010). The largest waves from distant and local tsunamis may pound the cliffs at Ecola State Park 8.8–18 m (29–58 ft) above the current shoreline and flood Cannon Beach, south of Tillamook Head (see the Cannon Beach map and brochure on the Oregon Tsunami Clearinghouse website).

Distant and local tsunamis will also flood the MCR and the riparian areas adjacent to the Lewis and Clark River. Fort Clatsop, above the flood zone, will serve as an assembly area for local neighbors and the Coast Guard Air Station Astoria. Netul Landing, although out of the distant tsunami evacuation zone, lies within the local tsunami evacuation zone (see the Youngs River Valley map and brochure on the Oregon Tsunami Clearinghouse website). The Astoria Column is well outside of the evacuation zone for either local or distant tsunamis (see the Astoria map and brochure on the Oregon Tsunami Clearinghouse website).

Megathrusts at the subduction zone contact between tectonic plates generate the most powerful earthquakes on earth, and these megathrust earthquakes trigger tsunamis. The Incorporated Research Institutions for Seismology (IRIS) website provides an excellent animation of three types of mega-earthquakes and subsequent tsunamis (https://www.iris.edu/hq/inclass/animation/subduction_zone_tsunamis_generated_by_megathrust_earthquakes). Examples from IRIS include the magnitude 9.0 Japan 2011 mega-earthquake, the magnitude 8.8 2010 Chile mega-earthquake, and the magnitude 9.2 Great Alaska Earthquake.

In Japan in 2011, rocks above the convergent plate boundary along a section of the Japan trench 500 km (300 mi) long and 200 km (120 mi) wide were compressed as much as 50 m (160 ft) before friction was overcome, releasing the overriding plate which generated a mega-earthquake as it slid abruptly up the fault. The earthquake generated a tsunami which raised seawater by 10 m (30 ft) at the leading edge of the overriding plate and rushed onshore within 20 minutes.

Both deformation and fault displacement were involved in the 2010 Chile tsunami that caused 123 deaths and major damage in coastal towns. Unlike the Japan earthquake, the leading edge of the overriding South American plate was not displaced. However, a section 600 km (360 mi) long and 130 km (78 mi) wide ruptured on the continental shelf. Internal deformation and compression uplifted the ocean floor 2–3 m (7–10 ft). The sudden uplift triggered the deadly tsunami.

The 1964 Great Alaskan Earthquake ruptured an 800 km (500 mi) long by 250 km (150 mi) wide section of the continental shelf on the eastern Aleutian Subduction Zone (https://earthquake.usgs.gov/earthquakes/eventpage/official19640328033616_30/executive). The mega-earthquake caused displacement along the fault of less than 2 m (7 ft) at the leading edge but over 9 m (30 ft) within the continental shelf. A steeply dipping splay fault branching off the main fault caused this sudden uplift of the sea floor. Because displacement on steeply dipping splay faults causes larger uplift of the ocean floor, larger tsunamis are generated, and the tsunami begins closer to shore, allowing less time to evacuate. Ground shaking in fiords and inlets also caused submarine landslides, which resulted in surges of seawater up to 50 m (160 ft) high that struck coastal towns. Any of these processes may trigger tsunamis at the CSZ.

Liquefaction

Liquefaction occurs where water-saturated sandy soil or artificial fill abruptly loses strength during earthquake shaking and behaves like quicksand. Liquefaction may cause catastrophic damage to shoreline and near-shore infrastructure. The moderately well-sorted beach sand at Cape Disappointment has a moderate liquefaction susceptibility, and without any infrastructure on the beach, destruction from liquefaction may not be a major concern for resource management. Because bedrock anchors Fort Columbia State Park and Dismal Nitch, these units have a very low liquefaction susceptibility (Palmer et al. 2004; see maps at the Washington Geologic Hazard Maps website, under “NEHRP Site Class and Liquefaction Susceptibility”).

According to the DOGAMI HazVu map, liquefaction susceptibility ranks high for Fort Clatsop, Netul Landing, Sunset Beach, and Seaside. Buildings and infrastructure in these units may be damaged. Moderate liquefaction are expected to occur on Clatsop Spit and Columbia Beach in Fort Stevens State Park as a result of earthquakes. Although the unconsolidated sediments of the Tillamook Head shoreline may experience low to moderate liquefaction, the infrastructure on the bedrock of Ecola State Park should not be damaged by liquefaction. The maps indicate that the docks and infrastructure in Astoria have a high liquefaction susceptibility, but the uplands upon which the Astoria Column rests will not be impacted.

Volcanic Activity

Volcanic hazards can put park resources, infrastructure, staff, and visitors at risk. These include hazards directly associated with an eruption such as falling ash, gasses, and lava flows, as well as those triggered by an eruption such as landslides. Although the prediction of volcanic eruptions is not precise, monitoring allows for detection of changes in a volcano’s behavior that precede impending eruptions. The Cascades Volcano Observatory (CVO) actively monitors all volcanic activity in the Pacific Northwest (https://volcanoes.usgs.gov/observatories/cvo/). The USGS Volcano Hazards Program (VHP) monitors volcanic activity in the Cascades and has the responsibility of issuing warnings of potential volcanic activity to civil authorities and affected communities. The VHP maintains seismic stations to monitor volcanic activity, issues short term warnings, researches how volcanoes work, and involves the community in educational and outreach programs (Stovall et al. 2016). The USGS VHP website (https://volcanoes.usgs.gov/index.html) includes current activity alerts and updates on potential volcanic hazards in the Pacific Northwest and throughout the Pacific Rim.

The Central Cascades Volcano Facilitating Committee updated their Central Cascades Volcano Coordination Plan in July 2019 (https://www.oregon.gov/OEM/Documents/Central_Cascades_Coordination_Plan.pdf). The plan enhances the region’s preparedness for emergencies and disasters and provides several Oregon counties, multiple State and Federal agencies, the Confederated Tribes of the Warm Springs Reservation, and the Klamath Tribes with response information for areas most likely impacted by a volcanic event. The Mount Hood Facilitating Committee prepared a Mt. Hood Coordination Plan in 2013 that focused on hazard planning efforts and offered recommendations on Mt. Hood volcanic event preparedness, response, and recovery to minimize impacts of volcanic activity on people, property, the environment, and the economy of the Pacific Northwest (https://www.oregon.gov/OEM/Documents/Mount_Hood_Volcano_Coordination_Plan.pdf). According to the Washington Department of Natural Resources and the Oregon DOGAMI HazVu maps, no volcanic hazards are mapped near any unit in Lewis and Clark NHP. Volcanic hazards are mapped in the Cascade Range, to the east.

However, past volcanic activity is responsible for several bedrock units in the park. Submarine lava flows from volcanic eruptions during the Eocene are captured in the bedrock of Cape Disappointment (**Tc**), Fort Columbia State Park (**Tbr**, **Tc**), Middle Village–Station Camp (**Tbr**, **Tc**), and Dismal Nitch (**Tbr**, **Tbf**) (GRI GIS data). Volcanic tuff has been incorporated in the sedimentary rock of the Smuggler Cove Formation (**Tsc**), exposed at Fort Clatsop and Ecola State Park (GRI GIS data). In Ecola State Park, intrusive basalt of the Grande Ronde Basalt (**Tgri**), a formation within the Columbia River Basalt Group, documents volcanic activity that occurred approximately 14 million to 15 million years ago (GRI GIS data).

In the *Geological Monitoring* chapter about volcanoes, Smith et al. (2009) described six vital signs and methodologies for understanding and monitoring volcanoes: (1) earthquake activity, (2) ground deformation, (3) emission at ground level, (4) emission of gas plumes and ash clouds, (5) hydrologic activity, and (6) slope instability. Lewis and Clark NHP is in a region of active volcanic and seismic activity, management is encouraged to consult the real-time data provided by the CVO and the PNSN for information concerning seismic activity associated with active volcanoes in the Cascade Range.

Landslide Hazards

Landslides are prevalent in the Pacific Northwest. For example, in the winter of 1996–1997, 9,500 landslides were reported in Oregon (Oregon Department of Geology and Mineral Industries 2008). Landslides may be triggered by CSZ earthquakes, but in general, saturation of slopes by abundant precipitation causes most landslides in the Pacific Northwest (Oregon Department of Geology and Mineral Industries 2008; Washington Geological Survey 2017a). In western Washington and Oregon, landslides typically occur during the winter months when rainfall or snowmelt adds significant weight to a slope and weakens the strength of the material to withstand the force of gravity. In addition to rainfall and intense shaking from CSZ earthquakes, rapid lowering of water levels and human activities such as vegetation removal, mining, excavation of the base of slopes, and leakage from pipes may trigger landslides. Easily weathered rock types and sandy or clay-rich soils are especially prone to landslides (Wieczorek and Snyder 2009; Washington Geological Survey 2017b).

In general, landslides may be categorized as either shallow or deep-seated. Shallow landslides tend to develop in unconsolidated sediment and soil, and often form slumps, flows, slides, rockfalls or topples. Deep-seated landslides, which are typically larger than shallow landslides, develop in bedrock. They may be slow moving, cover large areas, and devastate infrastructure and housing developments. They typically occur as translational or rotational slides or slides of large blocks of bedrock (Wieczorek and Snyder 2009; Washington Geological Survey 2017a). Wieczorek and Snyder (2009) and the Washington Geological Survey (2017a, b) provide more detail and graphics on the different types of slides.

The State of Washington provides a precipitation-induced shallow landslide hazard map that can be accessed daily to evaluate whether Cape Disappointment, Fort Columbia State Park, Middle Village–Station Camp, or Dismal Nitch is under a shallow landslide advisory, watch, or warning (https://www.dnr.wa.gov/slhfm). The map does not predict or forecast shallow landslides, nor does it forecast deep-seated landslides. The Washington Department of Natural Resources also maintains a Washington Geologic Information Portal website that documents mapped and inventoried landslides (https://geologyportal.dnr.wa.gov/#natural_hazards). The website provides a table of contents with specific hazards. Clicking on a hazard updates the map to include that hazard. As of August, 2019, the portal does not include any documented landslides in the park units in Washington, nor does the GRI GIS data include any mapped landslides in Cape Disappointment, Fort Columbia State Park, Middle Village–Station Camp, or Dismal Nitch. A small landslide occurred in the Dismal Nitch unit in February 2011, temporarily blocking Highway 401, however. As Wells (1989) points out, abundant rainfall results in heavy vegetation and deep weathering of bedrock, so that landslides have the potential to damage the Civil War dormitory and lighthouses at Fort Columbia State Park and Cape Disappointment.

In Oregon, high landslide potential is mapped in the Astoria highlands and the uplands west of Fort Clatsop Visitor Center, along the Fort to Sea Trail, and in Ecola State Park. In February 1961, heavy precipitation caused a significant landslide in Ecola State Park that involved an area ~915 m (~3,000 ft) long and 300 m (1,000 ft) wide (Allan et al. 2009). In 2017, landslides caused by heavy rains damaged trails and caused the park to temporarily close (Frankowicz 2017). Recurrent movement over the years has tilted trees, cracked pavement, and formed sag ponds. The basalt of Ecola State Park is underlain by massive landslide deposits. Substantial landslide deposits from the Pleistocene ice ages border small streams in the area, some only 5 m (15 ft) wide. Landsliding is possible on the dunes that are oriented parallel to the coast in Seaside, Sunset Beach, and Fort Stevens State Park, but landslide potential is moderate for these areas. The Statewide Landslide Information Layer for Oregon ("SLIDO"; https://gis.dogami.oregon.gov/maps/slido/) is an interactive map viewer showing historic landslide locations, as well as landslide hazards.

Ecola State Park is included in a DOGAMI landslide hazard mapping program that identifies coastal erosion hazard zones and potentially active coastal landslides (Allan et al. 2009). Resource managers may use these maps to estimate maximum block failure widths and establish the landward boundaries of erosion hazard zones. Results from the program indicate that Ecola State Park lies within "active" and "high" hazard zones. Within Ecola State Park and Lewis and Clark NHP in general, areas particularly susceptible to landslides are underlain by Astoria Formation mudstone (**Tac**), Smugglers Cove Formation (**Tsc**), and late Pleistocene landslide deposits (**Qls**) (GRI GIS data). Bluffs composed of basalt and resistant sandstone, such as those found at Tillamook Head, erode at an estimated rate of 0.03m/year (0.1 ft/year) (Allan et al. 2009).

Oregon and Washington have developed LIDAR (Light Detection and Ranging) remote sensing protocols to accurately map landslide deposits and generate landslide susceptibility maps (fig. 19; Burns and Madin 2009; Mickelson and Slaughter 2017). The protocols establish a standard for a GIS-based landslide inventory that includes interpretations of types, classification, and descriptions of landslides, as well as an ESRI file geodatabase template designed for easy and consistent data entry. Once landslide hazards have been identified on inventory and susceptibility maps, they can be assigned a risk factor and mitigation projects can be prioritized and implemented (Burns and Madin 2009).

In the *Geological Monitoring* chapter about slope movements, Wieczorek and Snyder (2009) described

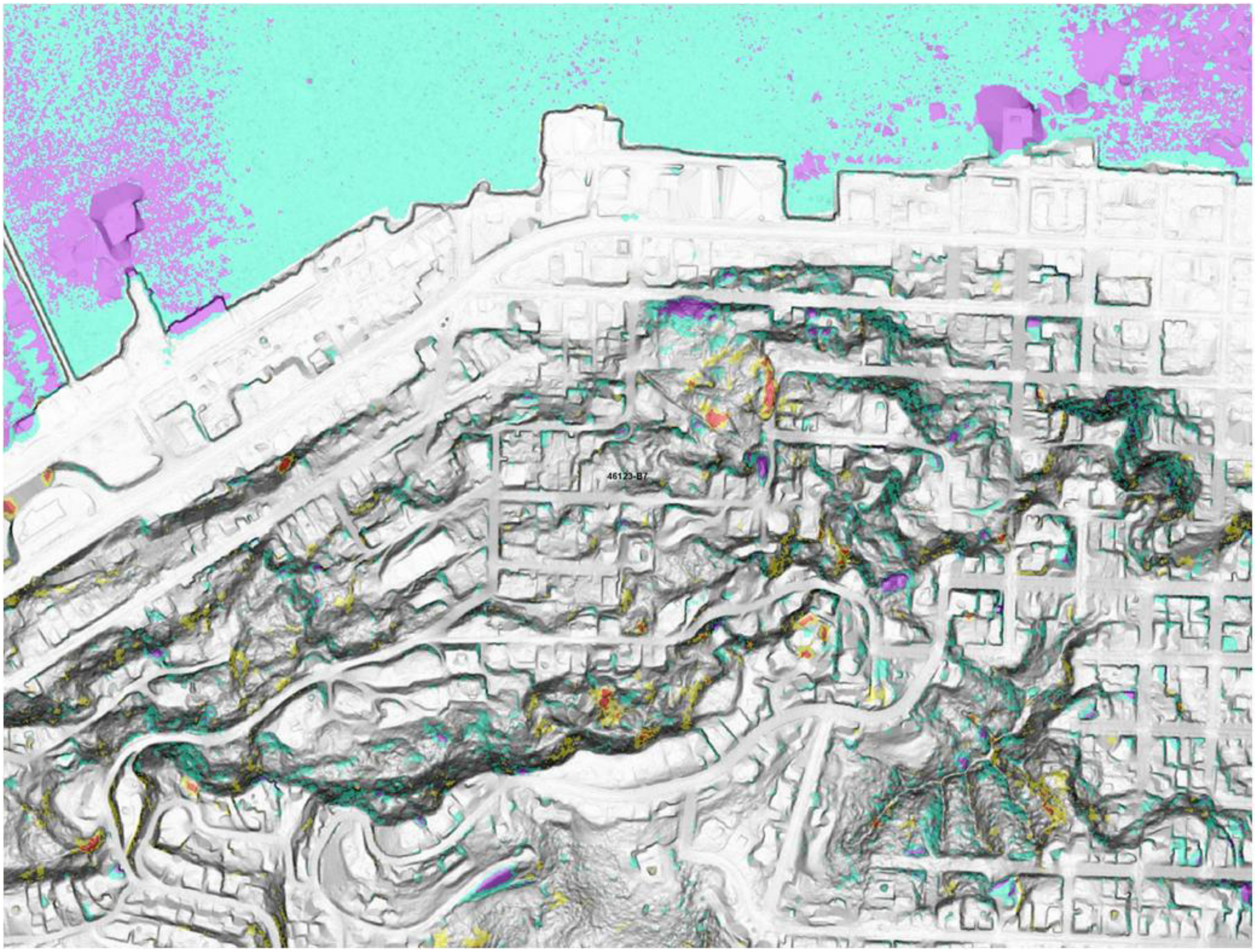


Figure 19. LIDAR image of Astoria, Oregon.
The rumpled topography, which includes almost all of Astoria, is a result of landslides. Darker shades fo gray indicate head scarps of landslides. Lighter gray colors indicate less impacted areas. For a detailed explanation of how LIDAR will be used to inventory landslides, see Burns and Madin (2009). The dock area is constructed on fine-grained, unconsolidated sediment, which is subject to liquefaction in the event of an earthquake. Courtesy of Ian Madin, DOGAMI (see Graham 2010).

five vital signs for understanding and monitoring slope movements: (1) types of landslide, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessment of landslide hazards and risks.

Flooding

According to Washington's Emergency Management Division flood website, floods cause more damage than any other natural hazard in Washington (https://mil.wa.gov/flood). However, Cape Disappointment, Fort Columbia State Park, Middle Village–Station Camp, and Dismal Nitch are in Pacific County, which the Emergency Management Division has not designated as among the more vulnerable counties subject to flooding.

According to the DOGAMI HazVu maps, parts of the Fort Clatsop unit, Netul Landing, and parts of Seaside reside within the effective FEMA 100-year flood area. In February 2017, several days of rain caused the rivers to overflow their banks and flood low-lying areas of Seaside with as much as 1.5 m (5 ft) of water. A storm surge in January 2018 swamped the Oregon coast with 9 m (30 ft) waves that spread driftwood and debris onto the main road in Seaside. Coastal towns of Coos Bay and Tillamook, south of Tillamook Head, have experienced flooding because of heavy winter rains combined with high tides (Dahl 2018). Seasonal flooding may occur along the Lewis and Clark River and has inundated parts of Fort Clatsop Road, Netul

Figure 20. Photographs of damage from slope movements caused by excessive rainfall. This type of damage to infrastructure may increase with increased precipitation and changes in the timing of precipitation because of increased temperatures in the Pacific Northwest. (A) A landslide at Dismal Nitch temporarily closed Highway 401 in February 2011. NPS photograph. (B) Heavy rains in January, 2016, opened this massive sinkhole off Highway 101 in southern Oregon. Photograph by the Oregon Department of Transportation, available at http://www.seattletimes.com/seattle-news/northwest/massive-sinkhole-opens-up-near-highway-along-oregon-coast/ (accessed 20 July 2017).

River Trail, and the kayak area at Netul Landing. Flooding may increase as rainfall frequency and intensity in the Pacific Northwest increases as climate changes (see "Issues Associated with Global Climate Change" section).

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

Paleontological Inventory

All paleontological resources are nonrenewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act (see Appendix B). As of August 2019, Department of the Interior regulations associated with the Act were awaiting surnaming.

No paleontological specimens are curated by Lewis and Clark NHP, and the park lacks a paleontological inventory and monitoring program. However, fossils from the geologic units in table 3, especially from the Astoria Formation (**Tac**), that have been discovered within and beyond the boundaries of the park and have contributed to the scientific understanding of evolutionary processes and distribution of these fossil groups (Fay et al. 2009). Recent land acquisitions over the past several years have resulted in even more strata within the park that may contain fossils. The paleontological resources in the park present opportunities for field surveys, a paleontological inventory, site monitoring, education, interpretation and future scientific research.

More than 30,000 archeological specimens are curated by the park, and some of these specimens may contain paleontological resources (Fay et al. 2009). For example, the park's largest archaeological site contained three pieces of fire cracked rock with shell impressions (Chris Clatterbuck, Chief of Resources, Lewis and Clark NHP, written communication, 1 July 2019). Fossils are often found within cultural resource context (Kenworthy and Santucci 2006). Identified as a key issue in the Foundation Document (NPS 2015), cultural resources in the park collections are in the process of being surveyed and cataloged. Preliminary recommendations for a paleontological resource management program at the park include (Fay et al. 2009):

- Documenting in situ fossil occurrences and monitoring significant sites at least once a year,
- Photo documenting any fossil occurrences observed by park staff while conducting their usual duties,
- Documenting paleontological resources found in the archeological collections, such as bone, shell, and wood fragments, and
- Reviewing field notes and journal entries by Captains Lewis and Clark for observations of in situ fossils, fossiliferous strata, or references to fossils that may have been collected and possibly delivered to Thomas Jefferson.

Future archeology excavations at Lewis and Clark NHP and field surveys of rock exposures should include a paleontological inventory. Such a field-based paleontological resource survey can provide detailed, site-specific descriptions and resource management recommendations that are beyond the scope of this report. Although a park-specific survey has not yet been completed for Lewis and Clark NHP, a variety of publications and resources provide park-specific or service wide information and paleontological resource management guidance. Fay et al. (2009) summarized fossils and some resource management challenges for all parks in the North Coast and Cascades Network (NCCN), including Lewis and Clark NHP.

In the *Geological Monitoring* chapter about paleontological resources, Santucci et al. (2009) described five methods and vital signs for monitoring in situ paleontological resources: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use. These methods may be used in tandem with any archeology survey conducted at a field site. Assistance may be provided to the park by the NPS Geologic Resources Division.

Cave Inventory

As of August 2019, cave or karst resources are documented in at least 159 parks. However, Lewis and Clark NHP is not on that list. Toomey (2009) defines a cave as a naturally occurring underground void, which includes solution caves, lava tubes, talus caves (a void among collapsed boulders), regolith caves (formed by soil piping), glacier caves (ice-walled caves), and the sea caves that have formed in the cliffs of Crescent Formation (**Tc**) at Cape Disappointment (fig. 13). Depending on the location(s) within Cape Disappointment State Park, the NPS and Washington State Parks and Recreation Commission may consider further inventory, documentation, monitoring, and management of the cave(s). The NPS Cave and Karst website (https://www.nps.gov/subjects/caves/index.htm), provides more information.

Issues Associated with Global Climate Change

Global climate change may be one of the more challenging issues for resource managers. Recognized as a key issue in the park's Foundation Document (NPS 2015), climate change affects all aspects of park management, including natural and cultural resource protection, park operations, and visitor experience. Potential resource threats include rising sea level, larger storm surges, flooding, and stronger storms that may increase coastal erosion. Infrastructure, wetlands, and park development may be damaged by these aspects of climate change. Park landscapes and riverscapes may be altered as weather patterns change, leading to accelerated weathering, deterioration, and loss of cultural resources (NPS 2015).

Natural resource changes that may affect the units in Lewis and Clark NHP include: (1) the timing of streamflow because of changes in precipitation and snowmelt, (2) beach erosion and inundation from sea level rise, and (3) increased ocean acidity (Melillo et al. 2014). Consequences from these changes involve competing demands for water resources, increasing wildfire, insect outbreaks, and tree diseases, all of which may negatively impact visitation and natural habitats in the park.

The North Coast and Cascades Network (NCCN) reports climate data (primarily precipitation and temperature) collected at Lewis and Clark NHP from three stations in Oregon and one station in Washington (Lofgren and Huff 2013). The National Centers for Environmental Information (formerly the National Climate Data Center) maintains temperature and precipitation records for these stations that are available online for Fort Clatsop, Astoria airport, Seaside, and Long Beach, Washington experimental station (https://www.ncdc.noaa.gov). Long-term climate analyses using multiple temperature and precipitation variables for many national park units were compiled by Monahan and Fisichelli (2014).

Water Resources

Regionally, ocean effects influence temperatures at the mouth of the Columbia River (Oregon Climate Change Research Institute 2012). Low temperatures occasionally reach freezing and below. High temperatures are generally less than 21°C (70°F) but can reach 27°C (into the 80s°F) (Lofgren and Huff 2013). According to data from the National Centers for Environmental Information, the mean maximum August temperature at Astoria airport from 1953-2015 was 21°C (69°F) and the mean minimum temperature was 13°C (37°F).

According to Bakker et al. (2019), most precipitation in the region arrives as rainfall brought by Pacific storms between October and April. At Astoria average annual rainfall was 175 cm (69 in) from 1953–2014. During the same period there was an average of 10.7 cm (4.2 in) of snow per year, although snowfall is rare. Summers are mostly dry, though fog is common. Precipitation amounts vary between watersheds, for example the Colewort Creek watershed receives approximately 202 cm (80 in)/year, while the Megler Creek watershed receives approximately 256 cm (100 in)/year (Bakker et al. 2019).

Various climate models document regional average temperature increases of about 0.8°C (1.5°F) since 1986 in the Northwest, including along the Washington and Oregon coasts where maritime influences cause less warming (IPCC 2007; Climate Impacts Group 2009; Karl et al. 2009; Vose et al. 2017). According to climate models prepared for the US Global Change Research Program (https://science2017.globalchange.gov/), temperatures in the Northwest are predicted to increase by 2.03–2.59°C (3.66–4.67°F) from 2036–2065 and from 2.77°C (4.99°F) to 4.73°C (8.51°F) from 2071–2100 (Vose et al. 2017). Climate change models for Washington state predict increases in average annual temperatures of 1.1°C (2.0°F) by the 2020s, 1.8°C (3.2°F) by the 2040s, and 2.9°C (5.3°F) by the 2080s (Climate Impacts Group 2009). A study of 289 natural resource parks administered by the NPS found that parks are at the extreme warm end of historical temperature distributions, and Lewis and Clark NHP is no exception (Monahan and Fisichelli 2014; NPS 2014).

A 2011 NPS study analyzing data from four weather stations within or adjacent to Lewis and Clark NHP found above-normal precipitation from October through May and unusually dry conditions in August (Lofgren and Huff 2013). There were several periods where temperatures were -7°C (low 20s°F) and snowfall occurred (Lofgren and Huff 2013). Compared to the years 1971–2000, annual precipitation at Astoria, Oregon, was 121% of normal and 111% of normal at Long Beach. Fort Clatsop received 116% (2.4 m [7.8 ft]) compared to data collected from 1998 to 2010. Wet conditions in the spring paralleled statewide average precipitation totals in Washington and Oregon where Washington reported the wettest spring conditions in 117 years and Oregon the second wettest spring.

Long-term changes in average precipitation have not yet been detected in the Pacific Northwest (Oregon Climate Change Research Institute 2012, Mote et al.

2014). Change predictions for the northwestern portion of Oregon indicate a possible decline of up to 20% under some emission scenarios, though estimates range from an increase of 23% to this minimum (Mote et al. 2014, Retallack et al. 2016). Though there is uncertainty regarding changes in annual precipitation, nearly all models predict that the seasonal distribution of precipitation will change, with greater relative change occurring in winter and less in summer (Mote et al. 2014, Retallack et al. 2016). An important result of changes in seasonal patterns with significant ecological implications is much earlier spring snowmelt (Vano et al. 2015). Storm intensity (water volume/time) is predicted to increase in the PNW, particularly in the summer, and in fact increases in intensity have been detected for the greater Portland, Oregon region during the period 1999-2015 (Bakker et al. 2019).

Gonzales et al. (2018) found a 17% per century decline in precipitation at the park from 1950–2010, but this trend was not statistically significant. They forecast an increase in precipitation ranging from 3% to 5% by 2100 (Gonzales et al. 2018; Bakker et al. 2019).

Sea Level Rise

According to the National Oceanic and Atmospheric Administration (NOAA), sea level rises because of two main factors: "(1) thermal expansion of ocean water due to increased sea surface temperature, and (2) input of water from the land such as ice caps in the southern hemisphere, melting glaciers, and water retained in rivers, aquifers, and lakes" (NOAA 2017a, p. 2). Global mean sea level (GMSL) is expected to rise from a 0.30 m (1.0 ft) to a potential extreme of 2.5 m (8.2 ft) by 2100 relative to 2000 GMSL (Mote et al. 2014; Sweet et al. 2017). However, uncertainties resulting from physical factors such as the rate of ice melt from Greenland and Antarctica, isostatic rebound from the Pleistocene ice ages, and local tectonic uplift and subsidence complicate the relationship between GMSL and regional variations in relative sea level (RSL) (Wong et al. 2014; Sweet et al. 2017).

Factors such as the GMSL rise, isostatic adjustment to past glaciers, local vertical movements of the land, and wind-driven 'pile-up' of water along the coast influence RSL along the Oregon and Washington coasts (Karl et al. 2009; Sweet et al. 2017). Isostatic adjustment to shrinking glaciers is projected to limit RSL rise in the Pacific Northwest (Sweet et al. 2017; Caffrey et al. 2018). In the late 20th century, tectonic uplift exceeded RSL rise over parts of the coast (Komar 1992). This relationship may change with increased global warming and a rise in GMSL. According to NOAA's sea level trends data, sea level at Garibaldi, Oregon, which is south of Cannon Beach, rises at a rate of 2.52 mm/year (0.099 in/year) based on monthly mean sea level data from 1970–2016, while sea level at Astoria has been decreasing at a rate of 0.2 mm/year (0.008 in/year) (NOAA 2017b). Although the Northwest coast is rising due to tectonic uplift, a CSZ earthquake, which is expected within the next few hundred years, would reverse centuries of uplift and, based on historical evidence, increase RSL rise by 1.0 m (3.3 ft) or more (National Research Council 2012; Mote et al. 2014).

According to Caffrey et al. (2018), estimates of sea level rise for Lewis and Clark NHP range from a minimum value of 0.1 m (4 in) in 2030 to a maximum value of 0.53 m (21 in) in 2100, depending on emissions scenario. An NPS sea level rise viewer (https://maps.nps.gov/slr/) provides a visualization of the Caffrey et al. (2018) data.

Immediate effects of sea level rise can be seen in the transition of ephemeral to permanent lakes in the interdunal swales in Lewis and Clark NHP. Inland from the coast, interdunal swales progress from dry nearest the ocean, intermittent lake, persistent lake, stream connected persistent lakes, and finally, permanent swamp. With rising sea level and subsequent rising groundwater tables near the coast, this progression may shift seaward, thus altering current habitat and ecosystem patterns (Graham 2010). Previously dry interdune swales are becoming permanent lakes.

According to Peek et al. (2015), 70% of the facilities ("assets") in Lewis and Clark NHP are considered at "high" exposure for 1 m of sea level rise while the remaining 30% are considered to be at "limited" exposure.

Inland and Coastal Flooding

The number of extreme precipitation events may increase by two to three times the historical average by the end of the 21st century. By mid-century in the Pacific Northwest, daily precipitation is expected to increase by 9–11%, depending on low versus high greenhouse gas emissions, and by the late century, daily precipitation is predicted to increase from 10% to over 19%, indicating a large increase in heavy precipitation days (Easterling et al. 2017).

Atmospheric rivers, which are long, narrow regions of moisture in the atmosphere that act like rivers in the sky, are expected to become more frequent and intense along the West Coast (Hagos et al. 2016; Kossin et al. 2017). While they offer a relief from drought, atmospheric rivers may also cause severe flooding, especially along coastal terrain. Between the last twenty years of the 20th and 21st centuries, the frequency of atmospheric river days that produce rain falling on land increased by 35%, and the frequency of associated extreme precipitation days increased by 28% (Hagos et al. 2016).

Along the coast, most damage is caused by the combination of storm surge at high tide, wave action, and wave runup (Sweet et al. 2017). During extreme storm events, wave runup has caused more damage than RSL rise over the last several decades. As RSL rises, high-water events are expected to increase the extent and depth of minor-to-major coastal flooding along the entire coast of North America (Sweet et al. 2017). By 2050, an average 8-fold increase in the annual number of floods exceeding the elevation of the current 100-year flood event is predicted to affect the contiguous US coastline. Such flooding will impact parts of the Fort Clatsop unit, Netul Landing, and parts of Seaside, which are all within the 100-year flood area. In addition, more than 57,000 ha (140,000 ac) of coastal lands in Washington and Oregon lie within 1 m (3 ft) of high tide (Mote et al. 2014). Rising sea level will inundate these areas more frequently in the future.

The recurrence intervals of minor tidal flooding (contemporary recurrence intervals are generally less than 1 year) will also increase over the next decades until they become a daily event (Sweet et al. 2017). Although coastal flooding will have its greatest impact along the mid- and southeast Atlantic, western Gulf of Mexico, California, and the Island States and Territories, moderate level flooding at most NOAA tide gauge locations will increase 25-fold (Sweet et al. 2017).

Coastal Erosion

Winter storms along the Oregon and southwestern Washington coast often generate individual waves with heights of 12–15 m (40–50 ft) (Komar 1992; Allan et al. 2009). These waves carry a tremendous amount of energy that can erode beaches and threaten coastal property and infrastructure. Erosion of Tillamook Headland has left pebbles and cobbles on the beach at Seaside. Although the construction of jetties at the MCR has decreased the sand supply to the beaches along the coast, the jetties had caused minimal erosion on the most northern Oregon coast by the end of the 20th century. In each of the littoral cells along the northernmost coast, the direction of longshore sand transport reverses with the season, so the net long-term drift at the turn of the century was estimated to be effectively zero (Komar 1992).

Sea level rise and an increase in storm intensity due to global climate change may have altered this stability, however. Strong El Niños may increase storm frequency even further, initiating severe beach erosion. The Southwest Washington Coastal Erosion Study, initiated in 1994, recognized regional sediment supply, sea level rise, preexisting topography, and bathymetry, which influences accommodation space, as the dominant controls on large-scale coastal change (Kaminsky and Gelfenbaum 2000; Allan et al. 2009). The large jetties at the MCR and Grays Harbor are now recognized as forcing local changes along the coast, which have directly and indirectly influenced adjacent shoreline accretion and erosion for distances of tens of kilometers and over time scales of several decades. The study showed how morphodynamic modeling can be used to predict future shoreline behavior based on data analysis and knowledge gained from past monitoring (Allan et al. 2009).

Climate models predict extensive coastal erosion with higher-than-normal sea levels and wave action (Sweet et al. 2017). The most damaging coastal hydraulic conditions occur when a storm surge at high tide combines with the dynamic wave action, which increases the chances of extensive coastal erosion. During extreme storm events, wave runup has become more of a factor than RSL along the Pacific Northwest coast.

Precipitation and Mass Wasting

Mass wasting events, such as landslides and slumps, are expected to increase in frequency and severity with global climate change. Increased winter rainfall raises concern about an increase in landslides on coastal bluffs, such as Tillamook Head. Saturated soils will increase, which may trigger more landslides. Increased frequency and/or severity of landslides may be especially problematic and damaging to infrastructure where development is combined with unstable slopes (fig. 20). Earlier snowmelt, increased rainfall, and less cohesive soils in clear-cut areas may also contribute to increased landslide susceptibility (Barik et al. 2017).

Adaptation Strategies

The NPS is focused on providing adaptation strategies for climate change in the national parks, including strategies involving coastal natural resources such as sand dunes found at Lewis and Clark NHP (Koslow et al. 2016). Shaped by wind and waves, beaches are dynamic ecosystems. Sea level rise increases coastal erosion and accelerates landward migration of the shorelines. Sand dunes protect habitats from wind and wave damage. As sea level rises, more frequent storm surges may lead to increased erosion and overwash events that will allow less time for the dunes to recover and stabilize.

General strategies for managing coastal ecosystems are presented in the 2016 *Coastal Adaptation Strategies Handbook* (Beavers et al. 2016). The handbook summarizes the current state of NPS climate adaptation and key approaches currently in practice or considered for climate change adaptation in coastal areas to guide adaptation planning in coastal parks. The chapters focus on policy, planning, cultural resources, natural resources, facility management, and communication/education. The handbook highlights processes, tools and examples that are applicable to many types of NPS plans and decisions. One chapter includes a case study of Hurricane Sandy response and recovery strategies including changes to infrastructure. Another chapter features practical coastal infrastructure information including cost per unit length of constructed features (including seawalls, beach nourishment, and nature-based features). The level of detail varies by topic depending on the state of research and practice in that field. Additional reference manuals that guide coastal resource management include *NPS Reference Manual #39-1: Ocean and Coastal Park Jurisdiction* (in development), which can provide insight for parks with boundaries that may shift with changing shorelines; and *National Park Service Beach Nourishment Guidance* (Dallas et al. 2012) for planning and managing nourishment projects.

For Lewis and Clark NHP, climate change adaptation strategies may include (NPS 2014):

- Characterizing park exposure to recent climate change in a vulnerability assessment.
- Developing plausible and divergent futures for use in a climate change scenario planning workshop.
- Synthesizing desired future conditions for use in a Resource Stewardship Strategy or other National Park Service management plan.
- Creating interpretive materials for communicating with local communities and park visitors.

Lewis and Clark NHP managers and partners are addressing these climate change issues by gathering information on the vulnerability of key resources and updating their sustainability plan based on new data (NPS 2015). Climate change vulnerability assessments are needed to understand species and habitat sustainability and to understand how climate change may alter landscapes and riverscapes.

The Cultural Resources Climate Change Strategy (Rockman et al. 2016) presents a vision and broad approach for managing impacts to and learning from cultural resources under modern climate change. The strategy sets four goals: (1) set the broad scope of cultural resources and climate change response by connecting the concepts of impacts and information with the four pillars of climate change response: science, adaptation, mitigation, and communication; (2) coordinate science, management, and communication to identify and improve understanding of the effects of climate change on cultural resources; (3) incorporate climate change into ongoing cultural resources research, planning, and stewardship; and (4) collaborate with partners to grow and use the body of knowledge and practice for cultural resources and climate change.

Coastal and Shoreline Engineering

Coburn et al. (2010) identified 12 coastal engineering projects in and immediately adjacent to Lewis and Clark NHP. These projects included four revetments, three jetties, two groins, one bulkhead, and two dredge/fill projects. This inventory of engineering projects was designed to: (1) help the NPS understand its resources, (2) establish baselines, (3) develop desired future conditions, (4) balance the protection of historic resources and infrastructure with the preservation of natural systems, and (5) improve post-storm response. These actions may improve the ability of the NPS to manage coastal parks according to NPS policies, which include allowing natural coastal processes in parks to continue without interference, except in cases that require protection of natural resources, park facilities, or historic properties. Some of these natural processes include erosion, shoreline migration, deposition, overwash, and inlet formation.

Jetties

Of the 12 coastal engineering projects identified by Coburn et al. (2010), the three jetties constructed at the MCR represent the most prominent engineering effort (fig. 14; table 4). According to Coburn et al. (2010), the jetties consist of twelve million tons of stone, and because of the jetties, more than 460 million cubic meters (600 million cubic yards) of sediment has been discharged to the ocean. In addition, 150 million cubic meters (190 million cubic yards) of sediment had been dredged from the MCR channel between 1904 and 2010. In 2010, the average annual amount of sand dredged from the MCR was 2.7 million cubic meters (3.5 million cubic yards).

According to the Portland District of the USACE, wave impact resulting from an abnormal number and size of storms accelerated degradation of the jetties between 2000 and 2005 (Coburn et al. 2010). Outer portions of the jetties are being undermined because the sand spits, upon which the jetties are built, are receding. Storm waves are also battering exposed, previously protected sections of the jetties because ocean-side beaches, which initially formed because of jetty construction, are receding. To avoid a potential jetty breach, the USACE initiated shorter-term interim repair at critical locations on the north and south jetties.

Figure 21. Photograph of the North Jetty. The North Jetty was completed in 1917 and has undergone repairs and rehabilitation several times since original construction. The current rehabilitation project by the USACE Portland District began in October 2014 and is scheduled to be complete in 2019. Photo by Billie Johnson, USACE, http://usaceportland.armylive.dodlive.mil/index.php/2014/08/mcr-north-jetty-access-restricted-beginning-fall-2014/ (accessed 2 October 2018).

The last critical repairs occurred to North Jetty in 2015, South Jetty in 2007 and Jetty A in 1962. The USACE has designed a long-term rehabilitation project to make the jetties more durable (Coburn et al. 2010). Further information including a timeline, documents and multimedia presentations, and updates may be obtained from the USACE Mouth of the Columbia River Jetty System Major Rehabilitation Project website (https://www.nwp.usace.army.mil/jetties/).

South Jetty: Clatsop Spit, OR.

Since its completion in 1895, the 7.2-km- (4.5 mi) long South Jetty has undergone several major repairs and continued maintenance to eliminate shoaling and re-establish a deep and dependable channel for navigation (Coburn et al. 2010). Incessant wave action had flattened the South Jetty to the low-water level by 1931 and had spread out the rock rubble so that the outer 4.4 km (2.6 mi) of the MCR was 61 m (200 ft) at low-water level (Coburn et al. 2010). By 1936, repairs had added 2.2 million tons of rock, resulting in retopping the South Jetty to 7.6 m (25 ft) above low water to within 1,000 m (3,300 ft) of the outer end of the jetty. Two methods were used to halt the disintegration of the seaward end of the jetty. First, the stones at the outer end were bound into an impregnable mass with the injection of 12,787 tons of hot asphaltic mastic. However, this failed to prevent the continued degradation of the jetty's outer end. A second, more effective method proved to be the construction above the low-water level of a solid concrete terminal. When completed, the South Jetty top width varied from 14 m (45 ft) to 21 m (70 ft) and rose 7.9 m (26 ft) above mean lower low water. The base of the outer portion measured approximately 110 m (350 ft) wide with a total height to the top of the jetty as much as 23 m (76 ft) (Coburn et al. 2010).

USACE interim repairs commenced on the South Jetty in 2006 with completion in 2007 (Coburn et al. 2010). The project, designed to prevent a jetty breach for 10 to 15 years, involved placing approximately 145,000 tons of jetty stone in two areas over a 1,600-m- (5,300-ft) section of the jetty. All the rock came from Martin Marietta's Beaver Lake Quarry in Skagit County, Washington, which quarries primarily meta-volcanic greenstone. The rocks ranged in size from 11 tons to about 20 tons, with the heavier rocks placed near the end of the jetty to protect against more severe wave action. The project re-established a width of 9 m (30 ft) at the top of the jetty, which was 7.6 m (25 ft) above the mean lower low water level (Coburn et al. 2010).

North Jetty: Peacock Spit, Cape Disappointment, WA.

Because the South Jetty resulted in a channel depth of only 10–11 m (33–36 ft), the USACE decided to construct the North Jetty so that the desired navigational depth of 12 m (40 ft) could be reached (Coburn et al. 2010). Construction of the 4.0-km- (2.5-mi) long North Jetty began in 1914 and was completed by May 1917 (fig. 14). When completed, the North Jetty had a top width of 7.6 m (25 ft) and was 8.5–9.8 m (28–32 ft) above mean lower low water. Combined, the North and South Jetties contained 9 million tons of stone. With the construction of the North Jetty at the MCR, however, sand supply at Cape Disappointment became an issue (table 4; Allan et al. 2009).

The North Jetty was repaired in 2005. In 2008, the USACE initiated an interim repair project to limit further damage caused by storms in 2007. Sand was added to Benson Beach at Cape Disappointment, north of the North Jetty. However, repairs to the North Jetty were again required beginning in 2014. Repairs are expected to be completed in 2019, at which time the beach will be reopened to visitors (fig. 21).

Jetty "A": Cape Disappointment, WA.

The 0.5-km- (0.3-mi) Jetty A was constructed by the USACE in 1939 (fig. 14). Approximately 5 km (3 mi) upriver from the tips of the North and South Jetties, Jetty A serves to direct flow away from the base of the North Jetty (Coburn et al. 2010).

Prior to the jetties, an abundant sand supply expanded the shorelines along southwestern Washington and northwestern Oregon at rates exceeding several meters per year (Allan et al. 2009). Following the construction of the North and South Jetties, shoreline change became dominated by sediment supply from the flanks of the ebb-tidal deltas rather than from the MCR. Sediment supply from both the Columbia River and ebb-tidal deltas now appear to be declining and may not be enough to maintain the existing regional configuration of the shoreline (Kaminsky et al. 2002). Currently, none of the sand that enters the Columbia River estuary may even be reaching the littoral environment. Proposals to increase the amount of sand removed from the Columbia River estuary may transform the estuary into a sink, rather than a source, of sand to the Columbia River littoral cell (Kaminsky et al. 2002).

The complex shoreline responses to changes in the littoral sand supply accent the significance of understanding shoreface morphology and sediment transport on a decadal scale (Kaminsky et al. 2002). Distribution of sediment supplied by the Columbia River and ebb-tidal deltas is influenced by the jetties at the estuary entrances and the upper and lower shorefaces. Updates to the original 2000 Southwest Washington Coastal Erosion Study continue to analyze the coastal system dynamics of the Columbia River littoral cell to support local, state, and federal decision-making, management strategies, land-use planning, resource allocations, and hazard reduction solutions (Allan et al. 2009). According to Kaminsky et al. (2002), global climate change and sea level rise may influence shoreline behavior, but these factors are not as significant as changes occurring to the sediment supply that have resulted from the past century.

Shoreline Stabilization along the Columbia River

Neither the Clatsop nor Chinook peoples who lived in the region nor the members of the Lewis and Clark Expedition would recognize the park units along the Columbia River. Modifications to stabilize the shoreline at Dismal Nitch (fig. 22), Middle Village–Station Camp, and Netul Landing have dramatically altered the sites (table 4). A small narrow-gauge railroad constructed from 1889 to 1906 between Ilwaco and Megler changed the shoreline and cliffs and had its terminus at the east end of the present day Dismal Nitch site. To protect the railroad from erosion, immense boulders were removed from the cliffs and placed in the river to create an embankment. A ferry landing also was built at Megler. In 1968-1969, the Dismal Nitch Safety Rest Area was built on filled land associated with the ferryboat landing. Additional rock fill and topsoil extended the existing embankment to the south. Demolition

Figure 22. Photograph of the rock revetment at Dismal Nitch.
The revetment is composed of boulders from the cliff that trapped the Corps of Discovery. Photograph from Coburn et al. (2010, figure 66).

of adjacent cliffs and imported material provided two thousand tons of riprap designed to protect the bank from erosion. To protect State Highway 101, the approximately 2,000 m (6,500 ft) of shoreline in the Middle Village–Station Camp unit was stabilized with a rock revetment. A riprap revetment stabilizes over 610 m (2,000 ft) of shoreline on either side of Fort Columbia. Shoreline stabilization projects at Netul Landing included a concrete bulkhead along 18 m (60 ft) of the Lewis and Clark River at the bus entrance, numerous pilings, and a small rock revetment north of the bulkhead (Coburn et al. 2010). In addition, the construction of dikes for agriculture, which started in the mid-1800s, has cut off over 90% of the historic floodplain from the Lewis and Clark River (Carla Cole, Natural Resource Program Manager, Lewis and Clark NHP, written communication, 23 April 2019).

Dredging

USACE dredging of the MCR has continued since 1904. From 1939 to 1999, dredging removed 2.5 million cubic meters (3.3 million cubic yards) of sediment per year (Coburn et al. 2010). In 2010, 3–4 million cubic meters (4–5 million cubic yards) of sand was dredged and transported to open water disposal sites, which were specified beginning in 1945. Currently, the USACE dumps the sand on the mid-shelf in water depths greater than 40 m (130 ft), bypassing the littoral zone. The MCR deep-draft navigation project is designed to maintain a 0.8-km- (0.5-mi) wide navigation channel that extends for about 10 km (6 mi) through the jettied entrance of the Columbia River and the Pacific Ocean. The channel extends about 5 km (3 mi) seaward and shoreward of the tip of the North Jetty. Since 1984, the

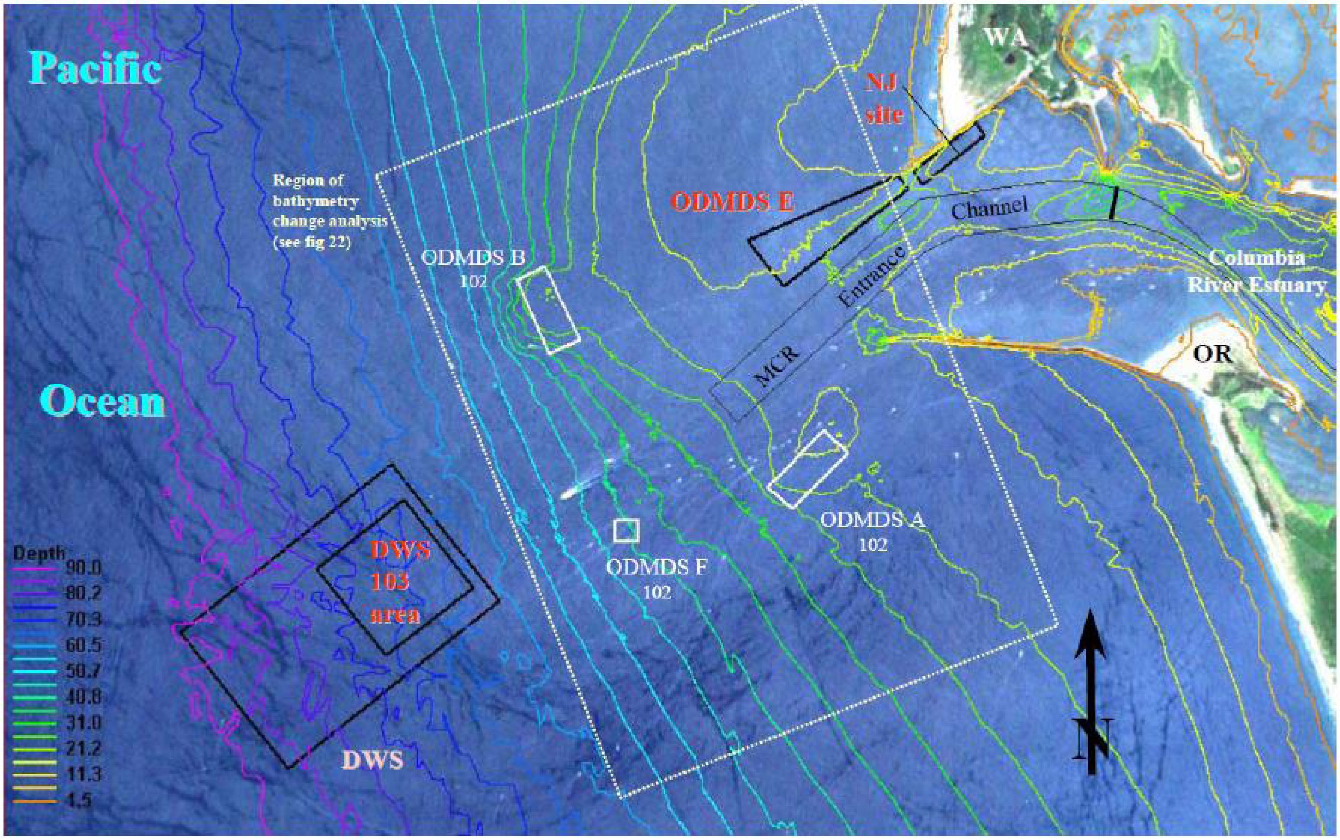


Figure 23. Map of USACE disposal areas for dredged material.
Ocean Dredged Material Disposal Sites (ODMDS) in red letters are new proposed sites (see table 4). The Deep Water Site (DWS) is located approximately 10 km (6 mi) from the mouth of the Columbia River. The DWS will be managed to allow maximum use of the other disposal sites to the maximum extent practicable or when weather or sea conditions preclude the safe use of the other disposal sites. Map is from Coburn et al. (2010, figure 71).

depth of the channel has been maintained at 17 m (55 ft) for the northerly 610 m (2,000 ft) of channel and 15 m (48 ft) for the southerly 200 m (640 ft) (Coburn et al. 2010).

From 1973 to 2003, approximately 50 million cubic meters (65 million cubic yards) of dredged sediment was deposited in Ocean Dredged Material Disposal Site (ODMDS) E, a designated area within Baker Bay (Coburn et al. 2010). Much of this material was transported north-northwest onto the crest and ocean-facing slope of Peacock Spit (fig. 14). The USACE speculates that this dredged material helped protect Peacock Spit and Benson Beach from a much higher rate of erosion (Coburn et al. 2010).

Sediment analysis of the littoral cell sediment budget shows that sediment supply has diminished due to regulated flow, dredging, and other anthropogenic changes to the Columbia River and MCR (Allan et al. 2009; Coburn et al. 2010). The sand supply diminished from 4.3 million cubic meters (5.6 million cubic yards) per year between 1878 and 1935 to 1.1 million cubic meters (1.4 million cubic yards) per year for the period 1958 to 1997 (Coburn et al. 2010). Because the dredged sand is transported to disposal sites on the mid-shelf, none of this sand delivered by the Columbia River to the estuary reaches the littoral environment (Kaminsky 2002; Kaminsky et al. 2002). Ongoing erosion of Peacock Spit, Clatsop Spit, and other nearshore regions at the MCR has resulted in increasing nearshore wave energy, increased shoreline erosion, and increased risk of jetty undermining and breaching (table 4). As of 2010, park management had encouraged the Corps to dump their dredge spoils on the north side of the North Jetty to nourish the beach and retard the rate of beach retreat. Once thought to kill Dungeness crabs, new research shows that Dungeness crabs are temporarily inconvenienced by sand dumping but return to their normal behavior soon after the event (Chris Clatterbuck, Chief of Resources, Lewis and Clark NHP, written communication, 5 May 2019).

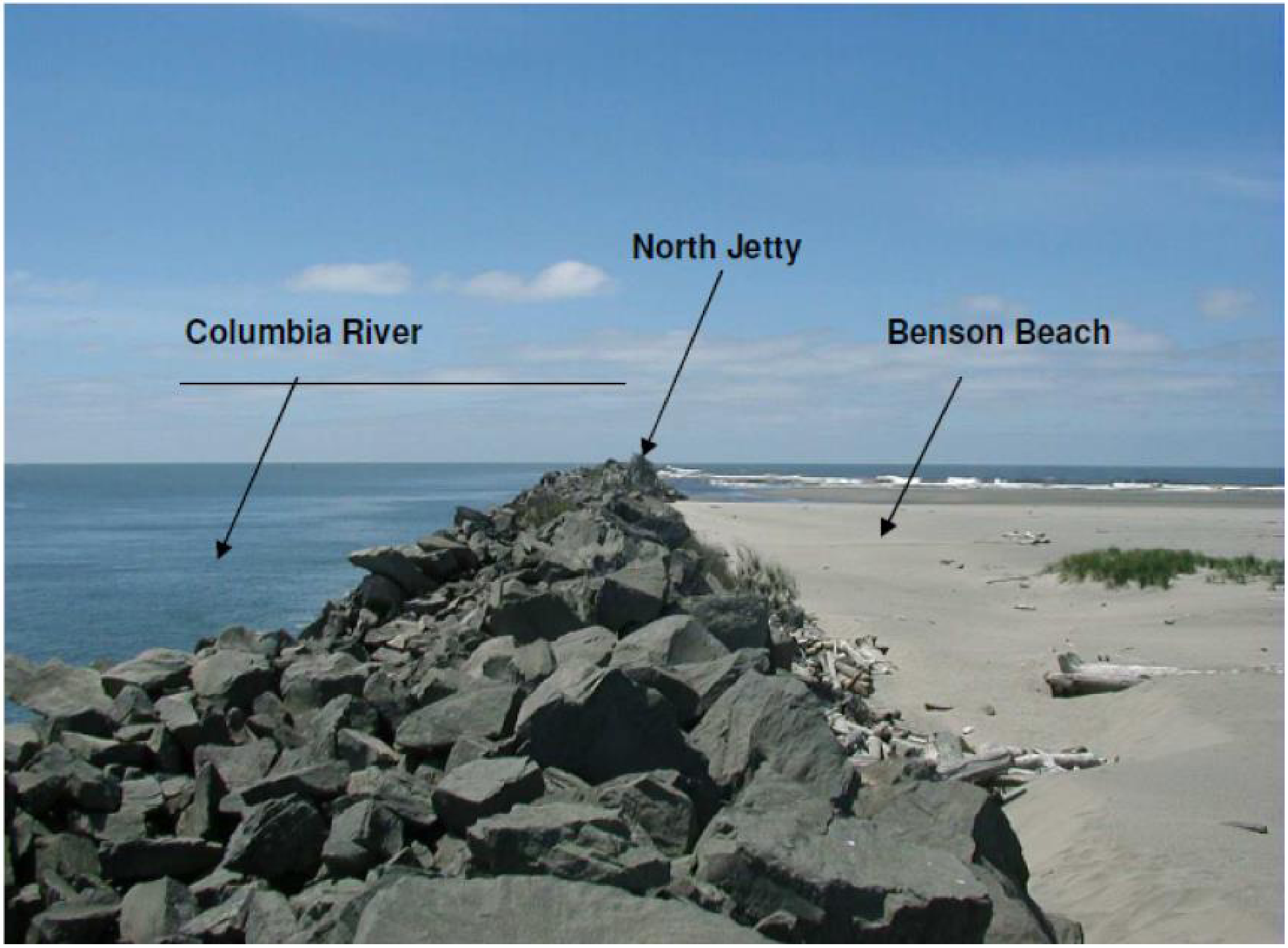


Figure 24. Photograph of beach nourishment on Benson Beach and the North Jetty, Cape Disappointment. Sand was added to the berm in 2008 because of storm damage in 2007. Further repairs to the North Jetty were required in 2014 because of storm damage. Photograph from Coburn et al. (2010, figure 72).

The USACE has proposed to continue maintaining the channel depth by dredging approximately 3.4–4.4 million cubic meters (4.5–5.7 million cubic yards) of sand per year from the MCR and placing it in the following ODMDS areas (fig. 23; table 4): (1) North Jetty site, (2) shallow water site, (3) deep water site, and (4) a prospective new disposal site south of the MCR South Jetty (Coburn et al. 2010). Approximately 76,000–380,000 cubic meters (100,000–500,000 cubic yards) of sand will be placed in the North Jetty site, which is near an older historical site. The USACE has been using this site since 1999 to protect the jetty from potential undermining. The shallow water site has been used since 1997 and is highly dispersive. Over 90% of the 21 million cubic meters (27 million cubic yards) of sand placed there in 2008 was removed by ocean currents. Most of the sand moved onto the ebb tidal shoal and to the north and northwest into the Southwest Washington littoral cell, dispersing to the Peacock Spit area and the littoral drift to the north. The material helps shore up the shoal beneath the North Jetty and minimizes the erosive impact of waves. The deep water site is located about 10 km (6 mi) off the coast of Oregon and allows maximum use of other disposal sites and offers an alternative if weather or sea conditions prohibit the use of other disposal sites. The proposed new site is located south of the South Jetty in an area that is losing between 67,000 and 206,000 cubic meters (88,000 and 270,000 cubic yards) of sand per year, exposing the pre-historic clay layers. Dredged sand would gradually build up this area and serve to break waves at a distance from the South Jetty, thus decreasing wave damage to the jetty (Coburn et al. 2010).

Beach Nourishment

Cape Disappointment State Park (Benson Beach, WA).

As part of the MCR project to maintain channel depth, approximately 33,000 cubic meters (43,000 cubic yards) of dredged sediment was deposited on Benson Beach in 2002 to determine the feasibility of placing sediment directly from a hopper dredge (Coburn et al. 2010). Because the sand berm area in Cape Disappointment State Park was damaged by storms in December 2007, the USACE interim project placed roughly 96,000 cubic meters (125,000 cubic yards) of dredged sediment in the intertidal area and uplands adjacent to the North Jetty to lessen the potential damage from future storms (fig. 24).

Nearshore Placement South of the South Jetty, OR.

In 2005, the USACE placed 26,189 cubic meters (34,254 cubic yards) of dredged material at a nearshore site on the ocean side of the South Jetty to restore the area and protect the South Jetty from adverse wave conditions (table 4).

SW Washington Littoral Drift Restoration.

As of 2010, the USACE was working with the State of Washington, Pacific County, the Southwest Washington Coastal Communities and the Lower Columbia Solutions Group on a proposed site for dredged material that would supply sand to the littoral drift system that moves sand northward along the Long Beach peninsula. If authority and funding are provided, up to 760,000 cubic meters (1,000,000 cubic yards) of sand could be placed in the intertidal zone on Benson Beach (Coburn et al. 2010).

Hydrocarbon Exploration

In 1979, economic quantities of gas were discovered near Mist, Oregon, roughly 50 km (30 mi) southeast of Astoria. No oil is associated with the gas. The gas reservoir in the Mist field occurs in the Clark and Wilson sandstone of the Cowlitz Formation, which is restricted to the eastern section of the Astoria Basin (fig. 25). The Cowlitz Formation pinches out before it reaches any Lewis and Clark NHP sites (Armentrout and Suek 1985; Niem et al. 1985). Deposited in a shallow marine environment, the Clark and Wilson sandstone grades laterally to the west into an impermeable, deep marine mudstone. Sedimentary strata near the park, such as the Smuggler Cove Formation (**Tsc**) and the Lincoln Creek Formation (**Tlc**), are either too impermeable, not buried deep enough, breached by erosion, or too thin and discontinuous to act as hydrocarbon reservoirs.

Faulting in the Mist field is complex. Normal and strike-slip faults are common, and an occasional high-angle reverse fault offsets the Clark and Wilson sandstone (Olmstead and Alger 1985). Many northwest-trending faults exhibit strike-slip movement, and vertical offsets along the faults may change drastically over short distances. East–west and northeast–southwest-trending faults are also present. Faults and unconformities may combine to trap the gas in the Mist field (Olmstead and Alger 1985).

Although hydrocarbon potential in and near Lewis and Clark NHP is extremely low, the Angora Peak Member and Youngs Bay Member of the Astoria Formation appear to be potential offshore hydrocarbon reservoirs (Cooper 1981; Niem et al. 1985). Petroleum exploration off the coast of southwestern Washington may be encouraged by the possibility of thermally mature sedimentary rocks in the accretionary wedge thrust beneath the forearc sequence. Exploration targets may exist beneath an inferred basal thrust or in upper plate sandstones, such as the sandstones at Megler (**Tsm**), which are immediately above such a thrust (Wells 1989). Hydrocarbon exploration on the continental shelf west of Seaside, Oregon, and Cape Disappointment could generate potential hazards for coastal units in southwestern Washington and northwestern Oregon, such as drilling accidents, hydrocarbon spills, viewscape deterioration, and/or habitat damage as dune traffic increases.

Hydrocarbon source rocks are also limited in southwestern Washington and northwestern Oregon. The Smuggler Cover Formation (**Tsc**) and Cannon Beach Member of the Astoria Formation (**Tac**) contain marginal to adequate gas-prone source rocks (Niem et al. 1985). Kerogen in these source rocks consists primarily of terrestrial organic matter that has proven to be low yielding, gas prone, and hydrogen deficient (Tissot and Welte 1978; Niem et al. 1985). Gas in the Mist field was thermally generated, perhaps from deeper parts of the Astoria Basin, and then the gas migrated up bedding planes until it was trapped below the impermeable Cowlitz Shale and against a normal fault (fig. 25; Armentrout and Suek 1985; Olmstead and Alger 1985).

In 1929, Union Oil Company of California drilled the McGowan No. 1 exploratory well in the Megler area in what is now Fort Columbia State Park (Glover 1947; McFarland 1983). The well was drilled to a depth of 1,337 m (4,385 ft). A slight gas show was reported, but no hydrocarbons were produced from the well.

As of 2005, only one of the more than 500 wells drilled in Washington found commercial amounts of hydrocarbons. That well was drilled in 1957 in Ocean City, approximately 96 km (60 mi) north of Cape Disappointment, by the Sunshine Mining Company. The well produced 12,500 barrels of oil before being shut down in 1961 (Brannon 2005). The NPS Geologic Resources Division Energy and Minerals branch can provide further assistance (https://www.nps.gov/subjects/energyminerals/index.htm).

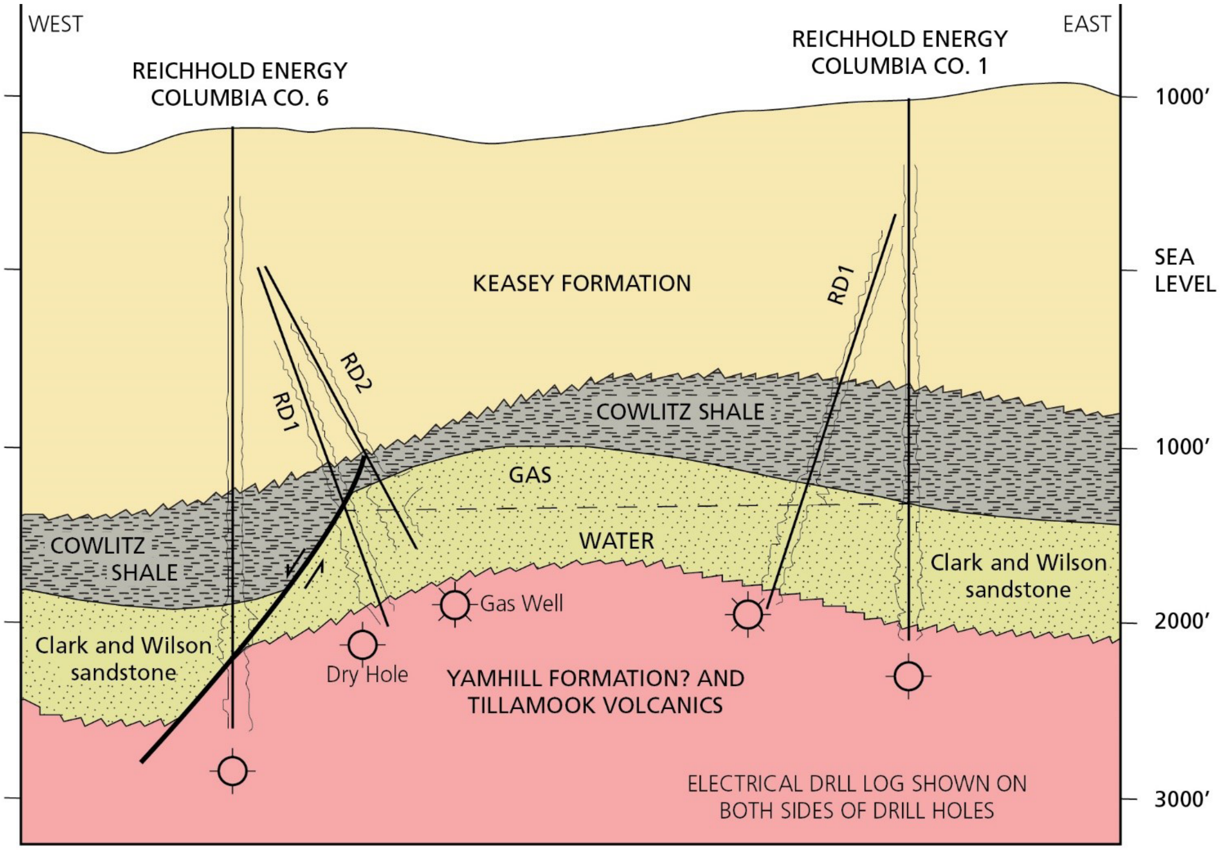


Figure 25. West–east cross-section through the Mist gas field.
The Cowlitz Formation consists of the Clark and Wilson sandstone, which contains the gas, and the Cowlitz Shale, which acts as a seal above the hydrocarbon reservoir. A normal fault acts as a lateral seal. The crooked lines represent unconformities, which bound the Cowlitz Formation. Diagram modified by Rebecca Port (NPS) from the Oregon DOGAMI Oil and Gas Investigation 10 by Olmstead and Alger (1985, fig. 5), http://www.oregongeology.org/pubs/ogi/OGI-10.pdf (accessed 21 July 2017).

Geologic Resource Management Assistance

The park's Foundation Document (NPS 2015) is a primary source of information for resource management within the park. A Natural Resource Condition Assessment is in progress as of summer 2019.

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

- Geologic heritage
- Active processes and hazards
- Energy and minerals management

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

Resource managers may find *Geological Monitoring* (Young and Norby 2009) useful for addressing geologic resource management issues. The manual provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. Each chapter covers a different geologic resource and includes detailed recommendations for resource managers, suggested methods of monitoring, and case studies.

The Geoscientists-in-the-Park and Mosaics in Science programs are internship programs to place scientists (typically undergraduate students) in parks to complete geoscience-related projects that may address resource management issues (see http://go.nps.gov/gip and http://go.nps.gov/mosaics). As of October 2018, no Geoscientists-in-the-Park or Mosaics in Science projects had been completed for Lewis and Clark NHP.

Table 4. Geologic resource management issues and hazards associated with the park.

Issue/Hazard	Description of issues and/or hazards
Cascadia Subduction Zone: Earthquakes (seismic activity)	Earthquakes trigger tsunamis, coastal area subsidence, landslides, and almost instantaneous liquefaction of fine-grained, unconsolidated sediment. A magnitude 9.0 CSZ earthquake would cause severe shaking in Fort Stevens State Park, Sunset Beach Recreation Area, Seaside, Ecola State Park, Fort Clatsop, and Astoria.
Cascadia Subduction Zone: Tsunamis	Local tsunamis from CSZ earthquakes can come onshore within 15 to 20 minutes. A tsunami from a magnitude 9.0 CSZ earthquake would flood Cape Disappointment, Fort Columbia, Fort Stevens, the Fort to Sea Trail, Netul Landing, and the Salt Works. Waves deflected by Tillamook Head may cause even more damage in Seaside.
Cascadia Subduction Zone: Liquefaction	Fort Clatsop, Netul Landing, Sunset Beach, and Seaside have a high liquefaction susceptibility ranking. Moderate liquefaction may occur on Clatsop Spit and Columbia Beach in Fort Stevens State Park.
Cascadia Subduction Zone: Volcanic Activity	No volcanic hazards are mapped in or near Lewis and Clark NHP, but past volcanic activity is responsible for several bedrock units in the park.
Landslide Hazards	Ecola State Park, the Astoria highlands, and the uplands west of Fort Clatsop Visitor Center, along the Fort to Sea Trail, have a high potential for landslides because of abundant precipitation.
Flooding	Parts of the Fort Clatsop unit, Netul Landing, and parts of Seaside reside within the effective FEMA 100-year flood area. Rising sea level and increased rainfall intensity may combine to increase flooding along the coast.
Paleontological Inventory	A paleontological inventory may include documenting in situ fossil occurrences and monitoring significant sites, photo documentation by staff during their regular duties, documenting paleontological resources in archeological collections, and reviewing the notes and journals of Lewis and Clark for references to fossils.
Cave Inventory	Resource managers may wish to establish a cave inventory for the sea caves that have formed in the cliffs of Crescent Formation (**Tc**) at Cape Disappointment.
Global Climate Change: Water Resources	Increased temperatures with global warming have changed the timing and amount of precipitation.
Global Climate Change: Sea Level Rise	Rising sea level (RSL) may cause shoreline regression. Global Mean Sea Level (GMSL) rise, isostatic adjustment to past glaciers, local vertical movements of the land, wind-driven 'pile-up' of water along the coast, and other factors create uncertainties about the overall effect of RSL. RSL and rising groundwater levels have caused usually dry interdunal swales near the ocean to become permanent swamps.
Global Climate Change: Inland and Coastal Flooding	Flooding along the Lewis and Clark River may increase as rainfall frequency and intensity in the Pacific northwest increases with global warming.
Global Climate Change: Coastal Erosion	Stronger storms may include larger storm surges, which will increase coastal erosion.
Global Climate Change: Precipitation and Mass Wasting	Landslides from increased precipitation and storm intensity may damage or destroy trails, roads, buildings, and other infrastructure, especially in active and high landslide hazard zones.

Table 4 (continued). Geologic resource management issues and hazards associated with the park.

Issue/Hazard	Description of issues and/or hazards
Coastal and Shoreline Engineering: Jetties	The USACE has a long-term rehabilitation program for the jetties and performs short-term interim repairs because storms have accelerated degradation of the jetties.
Coastal and Shoreline Engineering: Shore Stabilization on the Columbia River	Stabilization practices have resulted in rock revetments, embankments, and grass-covered areas along the Columbia River shoreline at Dismal Nitch, Middle Village–Station Camp, Fort Columbia, and Netul Landing. These modifications are designed to reduce erosion of the shore.
Coastal and Shoreline Engineering: Dredging	Dredging is one factor in diminished sediment supply to the Columbia River littoral cell. Dredging continues so the channel keeps open for navigation.
Coastal and Shoreline Engineering: North Jetty Proposed Disposal Site	Protection from potential undermining by wave action.
Coastal and Shoreline Engineering: Shallow Water Proposed Disposal Site	Dredged sand may enrich the Peacock Spit area, help shore up the shoal beneath the North Jetty, and minimize wave erosion.
Coastal and Shoreline Engineering: Deep Water Proposed Disposal Site	Allows for maximum use of other disposal sites or an alternative if weather or sea conditions prohibit the use of other disposal sites.
Coastal and Shoreline Engineering: South of South Jetty Proposed Disposal Site	Dredged sand may gradually replenish this area and serve to decrease wave damage to the jetty.
Coastal and Shoreline Engineering: Beach Nourishment	Placement of dredged sediment helps supply sand to Cape Disappointment and south of the South Jetty. This sediment helps alleviate the erosion caused by wave action during storms.
Hydrocarbon Exploration	Hydrocarbon exploration poses no immediate management issue. Offshore development may impose hazards associated with drilling, development, and transportation of hydrocarbons.

Figure 26. Paleogeographic maps of the Cascadia Subduction Zone off the coast of the Pacific Northwest. In the Paleogene, approximately 40 million years ago, the North American plate and the Farallon plate collided with each other at an oblique angle. By the Oligocene Epoch, 25 million years ago, the oblique convergence initiated the San Andreas Fault System. By the Miocene Epoch, 15 million years ago, the Farallon Plate had split into two plates: the Juan de Fuca Plate and the Cocos Plate, separated by the San Andreas Fault Zone. Today, the collision of the Juan de Fuca plate with North America has resulted in the Cascadia Subduction Zone off the coast of Oregon and Washington. Red stars indicate the approximate location of Lewis and Clark NHP. Annotations by the author and drafted by Trista Thornberry-Ehrlich (Colorado State University). Base paleogeographic maps are from the "North American Key Time Slices" © 2013 Colorado Plateau Geosystems Inc, used under license.

Geologic History

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

Over 500 million years of nearly-continuous tectonic collisions, explosive volcanic eruptions, fluctuating sea level, glaciers, and erosion shaped the current west coast of North America. Mountain-building episodes (orogenies) resulted in glaciated mountain ranges extending from Alaska to Mexico. Rocks and deposits within Lewis and Clark NHP record roughly 50 million years of this expansive West Coast geologic history that includes: (1) the evolution of the Cascadia Subduction Zone, (2) the construction of the Astoria Basin, (3) the eruption of vast quantities of basalt, and (4) sea level rise following the Pleistocene ice ages.

Evolution of the Cascadia Subduction Zone

By the beginning of the Cenozoic Era (fig. 2) and the extrusion of the submarine basalt that would become the Crescent Formation (**Tc**), the western margin of North America was colliding with the Farallon tectonic plate (fig. 26). The two tectonic plates collided with each other at an oblique angle, establishing a shearing motion that eventually created the San Andreas Fault Zone, approximately 25 million years ago. By the Miocene Epoch when the turbidites of the Lincoln Creek Formation (**Tlc**) were being deposited, the oblique convergence consumed the Farallon plate until it was left with two sections, the Juan de Fuca plate that was colliding with Washington and Oregon and the Cocos plate south of the San Andreas Fault, impinging on Latin America (fig. 26).

Today, the Oregon, Washington, and Vancouver Island crustal blocks are bounded by faults and deformed by the convergence of the Juan de Fuca and North American plates (McCaffrey et al. 2007). According to McCaffrey et al. (2007), shear deformation that extends northward from the California shear zone near Mendocino is being accommodated by the clockwise rotation of Oregon, and that rotation of the Oregon block has been relatively stable for the past 10–15 million years. The rigid crustal blocks are separated by two or three normal faults that slip at about 1 mm/year (0.04 in/year). Upper plate earthquakes occur if motion on the faults bounding the crustal blocks reaches 4.4±0.3 mm/year (0.17 in/year) (McCaffrey et al. 2007).

Off the coast of northern Oregon and southwestern Washington, major earthquakes triggered by movement on the Cascadia Subduction Zone fault occur approximately every 500–530 years (Goldfinger et al. 2012). The most recent major CSZ earthquake was the magnitude 9.5 earthquake that caused the tsunami of 1700 CE that destroyed the Japanese rice crop. The effect on any of the subsequent park units is known only through tribal oral history, but had they existed, the Salt Works, Cape Disappointment State Park, and Fort Stevens State Park could have been inundated by the tsunami.

Construction of the Astoria Basin

The oblique collision between the Farallon and North American plates opened the Astoria Basin in the Miocene (Niem and Niem 1985; Niem et al. 1985). Northwest-trending right-lateral and northeast-trending left-lateral strike-slip faults (fig. 4) and even older east-west strike-slip faults break the basin into a complex network of fault blocks (fig. 4; Niem and Niem 1985). The northwest- and northeast-trending faults reflect late middle Miocene north–south compression that produced wrench-faults, a type of strike-slip fault in which the fault surface is vertical, and the fault blocks move sideways past each other. Faulting, however, may have initiated in the late Eocene and then reactivated in the late middle Miocene (Niem et al. 1985).

About 20 million years ago, the oblique collision also opened the Portland Basin, which underlies Fort Vancouver National Historic Site (Graham 2019). Located east of the Astoria Basin, the Portland Basin may have formed as a broad syncline (concave fold) parallel to the Portland Hills anticline (convex fold) (Evarts et al. 2009).

The Eruption of Vast Quantities of Basalt

Complex subduction off the coast of Oregon and Washington dragged (and continues to drag) the Juan de Fuca plate beneath North America, generating magma and triggering massive volcanic eruptions (fig. 3). During the middle Miocene, rivers of basaltic lava poured from fissures that opened in the eastern portion of the Pacific Northwest crust (fig. 6). Low viscosity basaltic and andesitic lava flooded roughly 160,000 km^2 (63,000 mi^2) of the Pacific Northwest (USGS 2002; Liu and Stegman 2012). Over 300 high-volume individual lava flows and countless small flows accumulated into a thickness of over 1,800 m (6,000 ft) and collectively formed the Columbia River Basalt Group, which the Corps of Discovery passed as they traveled down the Columbia River, including the cliffs of the Columbia River Gorge.

Found at Ecola State Park, the Grande Ronde Basalt (**Tgri**) represents the most voluminous basaltic lava in the CRBG (Bishop 2003; Reidel and Tolan 2013). Eruptions of Grande Ronde Basalt resulted in 120 lava flows occurring from 16.5 million years ago to 15.6 million years ago. Lava covered almost 155,000 km^2 (60,000 mi^2) with a volume of lava estimated to be 146,000 km^3 (35,000 mi^3). As Ellen Bishop notes, this volume is enough to "construct a 7-foot thick, 100-foot-wide basalt freeway to the moon" (Bishop 2003, p. 141). Some individual flows poured across the flat Miocene landscape for more than 480 km (300 mi) to the Pacific coast where they invaded the Cannon Beach Member of the Astoria Formation (**Tac**, **Tac1**) (table 3) (Niem et al. 1985; Bishop 2003). The explosive interactions between hot basaltic lava and cold sea water can be seen in the shattered appearance of many of the basalt headlands along the northern Oregon coast and sea stacks, such as the picturesque Haystack Rock near Cannon Beach, part of the Ginkgo unit of the Frenchman Springs Member of the Wanapum Basalt of the Columbia River Basalt Group (Niem and Niem 1985; Wells et al. 2009).

Debate on the origin of the Columbia River basalts continues. A mantle plume hypothesis suggests that the outpouring of basalt was caused by mantle upwelling that gave rise to the Yellowstone hot spot. In this scenario, the mantle plume caused the rapid, radial migration (10–100 cm [4–40 in]/year) of volcanic activity approximately 15 million years ago, followed by a shearing off of the plume head as the hot spot tracked more slowly (1–5 cm [0.4–2 in]/year) across the Snake River Plain. Today, the mantle plume head is marked by high heat flow in the subsurface near the Idaho/Oregon border, young Cascade volcanism, and seismic activity that signals zones of higher temperatures (Camp and Ross 2004).

An alternative explanation for the origin of these flood basalts involves subduction of the Farallon Plate approximately 17 million years ago (Liu and Stegman 2012). The hypothesis suggests that as the Farallon Plate was subducted beneath the North American Plate, a piece broke off resulting in a 900-km- (600-mi-) long rupture in the area of present-day eastern Oregon and northern Nevada. Beginning about 16.6 million years ago, flood basalts erupted from this slab tear and spread from the Steens Mountain area of present-day eastern Oregon into northern Oregon, Washington, and the Snake River Plain in Idaho (fig. 6; Liu and Stegman 2012).

Sea Level Rise following the Pleistocene Ice Ages

In the Pleistocene (2.6 million to 11,600 years ago), the Cordilleran Ice Sheet expanded from coastal regions in present-day Alaska, along the Coast Mountains of present-day British Columbia, and into the region of present-day northern Washington, Idaho, and northwestern Montana (fig. 27). At times, the Cordilleran Ice Sheet coalesced with the western margin of the larger Laurentide Ice Sheet to cover a continuous area of over 4,000 km^2 (2,500 mi^2) across North America (Booth et al. 2004). During the Pleistocene ice ages, colossal outburst floods from Glacial Lake Missoula surged across eastern Washington, cascaded down the Columbia River Gorge, filled the Portland Basin with sediment, and backed up into the Willamette Valley before flowing out to sea (fig. 27). Extraordinary features resulting from these floods are summarized in the GRI reports for Fort Vancouver National Historic Site (Graham 2019) and Whitman Mission National Historic Site (Graham 2014).

The MCR, which now borders several units within Lewis and Clark NHP, emptied onto the continental shelf during the most recent ice age. When the continental ice sheets melted, average global sea level rose about 130 m (430 ft), reaching present sea level approximately 5,000 calendar years ago (Baker et al. 2010; Clark et al. 2014). Sea level rise off the coast of western North America, however, did not follow a uniform path, rising, for example, as if water was filling a bathtub. Rather, sea level rise at the end of the Pleistocene ice ages was influenced by crustal deformation (neotectonics), changes in global ocean volumes (eustasy), and the depression and rebound of the Earth's crust in response to ice sheets melting on land (isostasy) (Clark et al. 2014; Shugar et al. 2014). For archeologists, this non-uniform sea level rise has important implications regarding migration routes of First Americans. For geologists, non-uniform sea level rise influences the rate at which glacial and periglacial (the area adjacent to an ice sheet) deposits were buried by sediment transported by the Columbia River to the coast.

Furthermore, sea level rise varied from north to south along the coast. For example, isostasy played a bigger role in Alaska and British Columbia, which were covered by the Cordilleran Ice Sheet, than it did along the Oregon and Washington coast, which were not depressed by glacial ice (fig. 27; Dalrymple et al. 2012; Shugar et al. 2014). Farther north, relative sea level (RSL) fluctuated widely, at times higher than it is today, but RSL was never higher than it is today along the Washington and Oregon coast (Shugar et al. 2014). The MCR rose from about -100 m (-300 ft) about 18,000 years before present (BP) to approximately -75 m (-250 ft) around 16,500 years BP when the sea flooded isostatically depressed land, then dropped back to -100 m (-300 ft) around 13,000 years BP in response to isostatic uplift. Since 13,000 years BP, RSL has risen

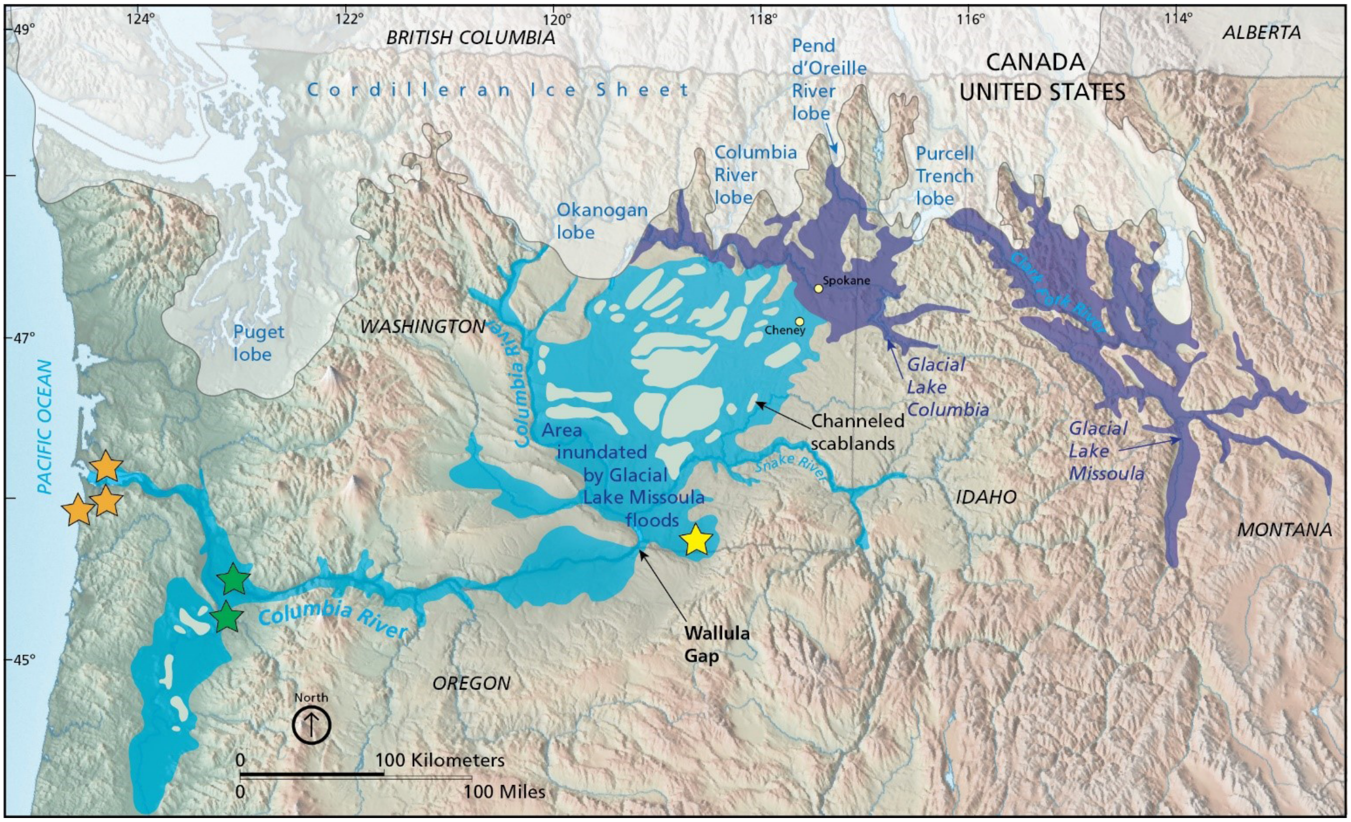


Figure 27. Map of the extent of Glacial Lake Missoula floodwaters and southern extent of the Cordilleran Ice Sheet.
During the Pleistocene ice ages, the Purcell Trench lobe of the Cordilleran Ice Sheet periodically flowed south, forming ice dams that blocked the Clark Fork River and allowing Glacial Lake Missoula to fill. When the ice dams failed, catastrophic floods swept across eastern Washington, through the Columbia River Gorge, and backed up into the Willamette Valley. The area affected by the Missoula floods is shown in light blue. Lake Lewis formed behind Wallula Gap and encompassed the present-day location of Whitman Mission National Historic Site (yellow star). The green stars indicate the approximate location of Fort Vancouver National Historic Site. Orange stars represent the general location of Lewis and Clark NHP sites. Graphic by Trista Thornberry-Ehrlich (Colorado State University) from a U.S. Geological Survey diagram, available at http://pubs.usgs.gov/sir/2005/5227/section5.html (accessed 30 July 2013). Base map by Tom Patterson (NPS), available at http://www.shadedrelief.com/physical/index.html (accessed 30 July 2013).

slowly to its present level (Dalrymple et al. 2012; Shugar et al. 2014).

Late-Holocene sea-level history records fluctuating RSL rise to the present datum. Long and Shennan (1998) contend that over the last 4,000 years, RSL rose about 3 m (10 ft) in Washington and 5 m (16 ft) in Oregon, probably in response to a north–south decline in the rate of isostatic rebound. Peat-mud couplet data from Coos Bay, Oregon, suggests that RSL rise was more punctuated with either an instantaneous subsidence due to seismic activity or rapid RSL rise about 4,800–4,500 years BP (Nelson et al. 1996).

The development of coastal dunes in Oregon is associated with two periods of post-glacial sea level fluctuations. During marine low-stand conditions in the late-Pleistocene, onshore winds transported sand across the exposed inner-continental shelf to the foothills of the coast range. Relatively rapid sea level rise in the early-Holocene submerged the inner-shelf, terminating the eolian cross-shelf sand supply. When transgression slowed in the middle-Holocene, waves transported abundant sand to the beaches of Oregon. Onshore wind velocities increased and delivered surplus sand inland to form extensive Holocene dune sheets (Peterson et al. 2007).

Currently, parts of northern California and the southern third of the Oregon coast are rising faster than the regional eustatic sea level rise of +2.28 mm/year (+0.09 in/year) (Komar et al. 2011). The differing trends in RSL may be due to the Cascadia Subduction Zone and associated complex tectonics of the region.

The landscape today consists of Tertiary exposures overlain by a variety of Quaternary deposits including shoreline sediments; fluvial, terrace, and estuarine deposits; and landslide material. Current depositional environments from Long Beach in Washington to Cannon Beach in Oregon include sand spits, beaches, elongate sand dunes, and low swales containing ponds or peat bogs. Old beach ridges that run parallel to the coast mark past positions of the shoreline as the influx of new sand built the beach seaward.

Geologic Map Data

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

Geologic Maps

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

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

Source Maps

The GRI team does not conduct original geologic mapping. The team digitizes paper maps and compiles and converts digital data to conform to the GRI GIS data model. The GRI GIS data set includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, cross sections, figures, and references. These items are included in the lewi_geology.pdf. The GRI team used the following sources to produce the GRI GIS data set for Lewis and Clark NHP. These sources also provided information for this report.

- Oregon Statewide Geologic Map: Ma et al. (2009)
- Correlation of Exploration Wells, Astoria Basin (Oregon): Martin et al. (1985)
- Geologic Map of the Astoria Basin (Oregon): Niem and Niem (1985)
- Geologic Map of the Cape Disappointment-Naselle River Area (Washington): Wells (1989)

GRI GIS Data

The GRI team standardizes map deliverables by using a data model. The GRI GIS data for Lewis and Clark NHP was compiled using data model version 2.1, which is available is available online (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 website (http://go.nps.gov/gri) provides more information about the program's products.

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

The following components are part of the data set:

- A GIS readme file (lewi_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information.
- Data in ESRI geodatabase GIS format;
- Layer files with feature symbology (table 5);
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information document (lewi_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures;
- An ESRI map document (lewi_geology.mxd) that displays the GRI GIS data; and
- A version of the data viewable in Google Earth (lewi_geology.kmz; table 5).

GRI Map Poster

A poster of the GRI GIS draped over a shaded relief image of the park and surrounding area is included with this report. Not all GIS feature classes are included on the poster (table 5). Geographic information and selected park features have been added to the poster. Digital elevation data and added geographic information are not included in the GRI GIS data, but are available online from a variety of sources. Contact GRI via their website for assistance locating these data.

Use Constraints

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

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features on the poster. Based on the source map scales of 1:100,000 (Niem and Niem 1985) and 1:62,500 (Wells 1989) and US National Map Accuracy Standards, geologic features represented in the geologic map data are expected to be horizontally within 51 m (167 ft) and 32 m (104 ft), respectively, of their true locations.

Table 5. GRI GIS data layers for Lewis and Clark NHP.

Data Layer	On Poster?	Google Earth Layer?
Geologic Cross Section Lines	Yes	No
Geologic Attitude and Observation Points	No	No
Dip of Beds in Borehole	No	No
Mine Point Features	No	No
Hazard Feature Lines	No	Yes
Linear Joints	No	Yes
Map Symbology (fault and fold symbology)	Yes	No
Faults	Yes	Yes
Folds	Yes	Yes
Geologic Line Features (conspicuous beds of glauconite)	No	Yes
Alteration and Metamorphic Area Boundaries (areas of contact metamorphism)	No	Yes
Alteration and Metamorphic Areas	No	Yes
Deformation Area Boundaries (areas of soft sediment deformation)	No	Yes
Deformation Areas	No	Yes
Geologic Contacts	Yes	Yes
Geologic Units	Yes	Yes

Literature Cited

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

Allan, J. C., and P. D. Komar. 2002. The wave climate of the eastern North Pacific; long-term trends and an El Nino/La Nina dependence. Pages 224–227 *in* G. Gellenbaum and G. M. Kaminsky, editors. Southwest Washington coastal erosion workshop report 2000. Open-File Report. US Geological Survey, Reston, Virginia.

Allan, J. C., and G. R. Priest. 2001. Coastal erosion hazard zones along the Clatsop Plains, Oregon: Gearhart to Fort Stevens. Open-File Report 0-01-04. Oregon Department of Geology and Mineral Industries, Portland, Oregon. https://www.oregongeology.org/pubs/ofr/O-01-04.pdf (accessed 14 August 2019).

Allan, J. C., R. C. Witter, P. Ruggiero, and A. D. Hawkes. 2009. Coastal geomorphology, hazards, and management issues along the Pacific Northwest coast of Oregon and Washington. Pages 495–519 *in* J. E. O'Connor, R. J. Dorsey, and I. P. Madin, editors. Volcanoes to Vineyards: geologic field trips through the dynamic landscape of the Pacific Northwest. Field Guide 15. Geological Society of America, Boulder, Colorado.

Ambrose, S. E. 1996. Undaunted courage: Meriwether Lewis, Thomas Jefferson, and the opening of the American West. Simon & Schuster, New York, New York.

Armentrout, I. M., and D. H. Suek. 1985. Hydrocarbon exploration in western Oregon and Washington. American Association of Petroleum Geologists Bulletin 69(4):627–643.

Atwater, B. F., S. Musumi-Rokkaku, K. Satake, Y. Tsuji, K. Ueda, and D. K. Yamaguichi. 2005. The orphan tsunami of 1700. Professional Paper 1707. USGS, Reston, Virginia. https://doi.org/10.3133/pp1707 (accessed 7 May 2019).

Baker, D., C. Peterson, E. Hemphill-Haley, and D. Twichell. 2010. Latest Pleistocene and Holocene (2–16 ka) sedimentation in the Columbia River Estuary, Oregon, USA. Marine Geology 273(1–4):83–95. https://doi.org/10.1016/j.margeo.2010.02.005 (access 7 May 2019).

Bakker, J. D., T. M. Hinckley, M-N. Wang, R. M. Mitchell, C. K. Gockel, K. Ewing, J. J. Lawler, S. Reichard, L. Jantarasami, M. McCain, and K. Y. Shea. 2010. Natural resource condition assessment for Lewis and Clark National Historical Park. Unpublished report. National Park Service, Fort Collins, Colorado.

Bakker, J. D., T. M. Hinckley, M-N. Wang, R. M. Mitchell, C. K. Gockel, K. Ewing, J. J. Lawler, S. Reichard, L. Jantarasami, M. McCain, and K. Y. Shea. 2019. Write up of methods. Natural resource condition assessment for Lewis and Clark National Historical Park, draft report. Draft Natural Resource Report. National Park Service, Fort Collins, Colorado.

Barik, M. G., J. C. Adam, M. E. Barber, and B. Muhunthan. 2017. Improved landslide susceptibility prediction for sustainable forest management in an altered climate. Engineering Geology 230:104–117. https://doi.org/10.1016/j.enggeo.2017.09.026 (accessed 7 September 2018).

Beavers, R., A. Babson, and C. Schupp, editors. 2016. Coastal adaptation strategies handbook. NPS 999/134090. National Park Service, Washington, DC. https://www.nps.gov/subjects/climatechange/coastalhandbook.htm (accessed 20 July 2017).

Bishop, E. M. 2003. In search of ancient Oregon. Timber Press, Portland, Oregon.

Booth, D. B., J. G. Troost, J. J. Clague, and R. B. Waitt. 2004. The Cordilleran Ice Sheet. Pages 17–45 in A. R. Gillespie, S. C. Porter, and B. F. Atwater, editors. The Quaternary period in the United States. Elsevier Ltd., San Francisco, California.

Bouma, A. H. 1962. Sedimentology of some flysch deposits, a graphic approach to facies interpretation. Elsevier, Amsterdam, The Netherlands.

Braile, L.W. 2009. Seismic monitoring. Pages 229–244 in R. Young, R. and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring (accessed 27 July 2017).

Brannon, D. 2005. Oil exploration in Washington. Essay 7446. HistoryLink.org Online Encyclopedia of Washington State History. http://www.historylink.org/File/7446 (accessed 29 July 2018).

Brocher T. M., J. R. Filson, G. S. Fuis, P. J. Haeussler, T. L. Holzer, G. Plafker, and J. L. Blair. 2014. The 1964 Great Alaska Earthquake and tsunamis—a modern perspective and enduring legacies. Fact Sheet 2014-3018. US Geological Survey, Menlo Park, California. https://pubs.er.usgs.gov/publication/fs20143018 (accessed 2 August 2018).

Burns, W. J., and I. P. Madin. 2009. Protocol for inventory mapping of landslide deposits from Light Detection and Ranging (lidar) imagery. Special Paper 42. Oregon Department of Geology and Minerals Industry, Portland, Oregon. https://www.oregongeology.org/pubs/dds/slido/sp-42_onscreen.pdf (accessed 5 September 2018).

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. http://go.nps.gov/geomonitoring (accessed 27 July 2017).

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 Series NPS/NRSS/NRR—2018/1648. NPS Climate Change Research Program, Fort Collins, Colorado. https://www.nps.gov/subjects/climatechange/sealevelchange.htm (accessed 31 August 2018). Associated sea level rise viewer: https://maps.nps.gov/slr/.

Camp, V. E., and M. E. Ross. 2004. Mantle dynamics and genesis of mafic magmatism in the intermontane Pacific Northwest. Journal of Geophysical Research 109 (B8):1–14. http://www.largeigneousprovinces.org/sites/default/files/CRBplume.pdf (accessed 02 April 2017).

Clark, J., J. X. Mitrovica, and J. Alder. 2014. Coastal paleogeography of the California—Oregon—Washington and Bering Sea continental shelves during the latest Pleistocene and Holocene: implications for the archaeological record. Journal of Archaeological Science 52:12–23. https://ir.library.oregonstate.edu/concern/articles/f1881n48q (accessed 1 August 2017).

Climate Impacts Group. 2009. The Washington climate change impacts assessment. M. M. Elsner, J. Littell, and L. W. Binder, editors. Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle, Washington. http://www.cses.washington.edu/db/pdf/wacciareport681.pdf (accessed 19 July 2017).

Coburn, A. S., A. D. Griffith, and R. S. Young. 2010. Inventory of coastal engineering projects in coastal national parks. Natural Resource Technical Report NPS/NRPC/GRD/NRTR— 2010/373. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2165163 (accessed 30 August 2018).

Cooper, D. M. 1981. Sedimentation, stratigraphy, and facies variation of the lower to middle Miocene Astoria Formation in Oregon. Dissertation. Oregon State University, Corvallis, Oregon. https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/js956k57f (accessed 30 August 2018).

Dahl, K. 2018. Sea level rise will make Oregon's existing flooding problems worse. Union of Concerned Scientists. https://blog.ucsusa.org/kristy-dahl/sea-level-rise-will-make-oregons-existing-flooding-problems-worse (accessed 30 August 2018).

Dallas, K., J. Eshleman, and R. Beavers. 2012. National Park Service beach nourishment guidance. Natural Resource Technical Report NPS/NRSS/GRD/NRTR—2012/581. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/DownloadFile/455109 (accessed 19 August 2019).

Dalrymple, R.A., L. C. Breaker, B. A. Brooks, D. R. Cayan, G. B. Griggs, W. Han, B. P. Horton, C. L. Hulbe, J. C. McWilliams, P. W. Mote, T. Pfeffer, D. J. Reed, and C. K. Shum. 2012. Sea-level rise for the coasts of California, Oregon, and Washington: past, present, and future. The National Academies Press, Washington, DC. http://www.ecy.wa.gov/climatechange/docs/ipa_slr_nrcfullreport.pdf (accessed 1 August 2017).

Deur, D. 2016. Empires of the turning tide: a history of Lewis and Clark National Historical Park and the Columbia Pacific region. Pacific West Region: Social Science Series Publication Number 2016-001. National Park Service, Seattle, Washington. https://www.nps.gov/lewi/learn/historyculture/upload/Empires.pdf (accessed 30 August 2018).

DeVoto, B., editor. 1953. The journals of Lewis and Clark. Houghton Mifflin Company, New York, New York.

Easterling, D. R., K. E. Kunkel, J. R. Arnold, T. Knutson, A. N. LeGrande, L. R. Leung, R. S. Vose, D. E. Waliser, and M. F. Wehner. 2017. Pages 207–230 *in* D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock, editors. Climate Science Special Report: Fourth National Climate Assessment, Volume I. U.S. Global Change Research Program, Washington, DC. https://science2017.globalchange.gov/chapter/7/ (accessed 27 August 2018).

Eungard, D. W., C. Forson, T. J. Walsh, E. Gica, and D. Arcas. 2018. Tsunami hazard maps of southwest Washington—Model results from a ~2,500-year Cascadia subduction zone earthquake scenario. Map Series 2018-01, 4 sheets, scale 1:48,000, 11 p. text. Washington Geological Survey, Seattle, Washington. http://www.dnr.wa.gov/publications/ger_ms2018-01_tsunami_hazard_southwest_washington.zip (accessed 15 August 2018).

Evarts, R. C., J. E. O'Connor, R. E. Wells, and I. P. Madin. 2009. The Portland Basin: a (big) river runs through it. GSA Today 19(9):4–10. https://www.geosociety.org/gsatoday/archive/19/9/article/i1052-5173-19-9-4.htm (accessed 30 August 2018).

Fay, L. C., J. P. Kenworthy, and V. L. Santucci. 2009. Paleontological resource inventory and monitoring: North Coast and Cascades Network. Natural Resource Technical Report NPS/NRPC/NRTR–2009/250 (September 2009). National Park Service, Natural Resource Program Center, Fort Collins, Colorado.

Frankowicz, K. 2017. Slip slidin' away. The Astorian. Astoria, Oregon. 12 May 2017. https://www.dailyastorian.com/archives/gazette/news/slip-slidin-away/article_a745a2f3-8710-5b80-b174-42b6d9e0391b.html (accessed 7 May 2019).

Glover, S. L. 1947. Oil and gas exploration in Washington. Information Circular 15. Department of Conservation and Development, Olympia, Washington. http://www.dnr.wa.gov/publications/ger_ic15_oil_gas_exploration.pdf (accessed 29 July 2018).

Goldfinger, C., C. H. Nelson, A. E. Morey, J. E. Johnson, J. R. Patton, E. Karabanov, J. Gutiérrez-Pastor, A. T. Eriksson, E. Gràcia, G. Dunhill, R. J. Enkin, A. Dallimore, and T. Vallier. 2012. Turbidite event history—methods and implications for Holocene paleoseismicity of the Cascadia Subduction Zone. Professional Paper 1661–F. US Geological Survey, Washington, DC. https://pubs.usgs.gov/pp/pp1661f/ (accessed 16 July 2017).

Gonzalez, P., F. Wang, M. Notaro, D. J. Vimont, and J. W. Williams. 2018. Disproportionate magnitude of climate change in United States national parks. Environmental Research Letters 13. https://iopscience.iop.org/article/10.1088/1748-9326/aade09 (accessed 7 May 2019).

Graham, J. 2010. Geologic resources inventory scoping summary: Lewis and Clark National and State Historical Parks, Oregon and Washington. National Park Service, Geologic Resources Division, Denver, Colorado. http://go.nps.gov/gripubs (accessed 8 August 2019).

Graham, J. P. 2014. Whitman Mission National Historic Site: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2014/839. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs (accessed 8 August 2019).

Graham, J. P. 2019. Fort Vancouver National Historic Site: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2019/1887. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs (accessed 8 August 2019).

Haeussler, P., W. Leith, D. Wald, J. Filson, C. Wolfe, and D. Applegate. 2014. Geophysical advances triggered by 1964 Great Alaska Earthquake. EOS 95 (17):141–142. https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/2014EO17 (accessed 2 August 2018).

Hagos, S. M., L. R. Leung, J.-H. Yoon, J. Lu, and Y. Gao. 2016. A projection of changes in landfalling atmospheric river frequency and extreme precipitation over western North America from the Large Ensemble CESM simulations. Geophysical Research Letters 43:1357–1363. https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/2015GL067392 (accessed 4 September 2018).

IPCC. 2007. Climate change 2007: synthesis report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Pages 1–104 in R. K. Pachauri and A. Reisinger, editors. Intergovernmental Panel on Climate Change (IPCC) Core Writing Team. Geneva, Switzerland. http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_full_report.pdf (accessed 19 July 2017).

Kaminsky, G. M. 2002. A review of Columbia River dredging: past practices and recent proposals. Pages 53–60 *in* G. R. Gelfenbaum and G. M. Kaminsky, editors. The Southwest Washington coastal erosion workshop report 2000. Open-File Report 02-229. US Geological Survey, Reston, Virginia. https://pubs.usgs.gov/of/2002/0229/pdf/of02-229.pdf (accessed 8 August 2017).

Kaminsky, G. M., M. C. Buijsman, P. Ruggiero, and G. Gelfenbaum. 2002. An integrated contemporary sediment budget for the Columbia River Littoral Cell. Pages 244–252 *in* G. R. Gelfenbaum and G. M. Kaminsky, editors. The Southwest Washington coastal erosion workshop report 2000. Open-File Report 02-229. US Geological Survey, Reston, Virginia. https://pubs.usgs.gov/of/2002/0229/pdf/of02-229.pdf (accessed 8 August 2017).

Kaminsky, G. M., and G. Gelfenbaum. 2000. The southwest Washington coastal erosion study: a scientific research project to address management-scale objectives. Coasts at the Millennium. Coastal Society 17th Conference, Portland, Oregon. http://www.ecy.wa.gov/programs/sea/swces/products/publications/papers/kaminsky_tcs00.pdf (accessed 7 August 2017).

Karl, T. R., J. M. Melillo, and T. C. Peterson, editors. 2009. Global climate change impacts in the United States. Cambridge University Press, Cambridge, United Kingdom. https://nca2009.globalchange.gov/northwest/index.html (accessed 19 July 2017).

Kenworthy, J. P. and V. L. Santucci. 2006. A preliminary investigation of National Park Service paleontological resources in cultural context: Part 1, general overview. Pages 70–76 *in* S. G. Lucas, J. A. Spielmann, P. M. Hester, J. P. Kenworthy, and V. L. Santucci, editors. America's antiquities: 100 years of managing fossils on federal lands. Bulletin 34. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico. https://www.nps.gov/subjects/fossils/thematic-inventories.htm (accessed 8 August 2019).

Komar, P. D. 1992. Ocean processes and hazards along the Oregon coast. Oregon Geology 54(1):1–20.

Komar, P. D., J. C. Allan, and P. Ruggiero. 2011. Sea level variations along the US Pacific Northwest coast: tectonic and climate controls. Journal of Coastal Research 27:808–823.

Koslow, M., A. Babson, and C. Schupp. 2016. Chapter 4: Natural Resources. Pages 29–44 *in* R. Beavers, A. Babson, and C. Schupp, editors. Coastal adaptation strategies handbook. NPS, Geologic Resources Division, Lakewood, Colorado and NPS Northeast Region, Narragansett, Rhode Island. https://www.nps.gov/subjects/climatechange/coastalhandbook.htm (accessed 8 August 2019).

Kossin, J. P., T. Hall, T. Knutson, K. E. Kunkel, R. J. Trapp, D. E. Waliser, and M. F. Wehner. 2017. Extreme storms. Pages 257–276 in D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock, editors. Climate Science Special Report: Fourth National Climate Assessment, Volume I. US Global Change Research Program, Washington, DC. https://science2017.globalchange.gov/chapter/9/ (accessed 4 September 2018).

Lancaster, N. 2009. Aeolian features and processes. Pages 1–25 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring (accessed 27 July 2017).

Liu. L., and D. R. Stegman. 2012. Origin of Columbia River flood basalt controlled by propagating rupture of the Farallon slab. Nature 482:386–390.

Lofgren, R., and M. Huff. 2013. North coast and Cascades network climate monitoring report: Lewis and Clark National Historical Park; water year 2011. Natural Resource Data Series NPS/NCCN/NRDS—2013/537. National Park Service, Ashford, Washington. https://irma.nps.gov/DataStore/Reference/Profile/2202911 (accessed 8 August 2019).

Long, A. J., and I. Shennan. 1998. Models of rapid relative sea-level change in Washington and Oregon, USA. Holocene 8:129–142.

Lord, M. L., D. Germanoski, and N. E. Allmendinger. 2009. Fluvial geomorphology: Monitoring stream systems in response to a changing environment. Pages 69–103 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring (accessed 27 July 2017).

Ma, L., I. P. Madin, K. V. Olson, R. J. Watzig, R. E. Wells, A. R. Niem, and G. R. Priest. 2009. Oregon geologic data compilation (OGDC)—Release 5. Oregon Department of Geology and Mineral Industries, Portland, Oregon. http://www.oregongeology.org/sub/ogdc/index.htm (accessed 3 August 2017).

Madin, I. P. 2009. Geologic map of the Oregon City 7.5' quadrangle, Clackamas County, Oregon (scale 1:24,000). Geologic Map Series GMS-119. Oregon DOGAMI, Portland, Oregon. http://www.oregongeology.org/pubs/gms/p-GMS.htm (accessed 02 April 2017).

Madin, I. P., and M. M. Mabey, editors. 1996. Earthquake hazard maps for Oregon. DOGAMI Geological Map GMS-100. Oregon DOGAMI, Portland, Oregon. http://www.oregongeology.org/pubs/gms/GMS-100.pdf (accessed 31 July 2018).

Martin, M. W., M. M. Kadri, A. R. Neim, and D. R. McKeel. 1985. Correlation of exploration wells, Astoria Basin Northwestern Oregon. Oil and Gas Investigations 14. Plate 2 of 2. Oregon Department of Geology and Mineral Industries, Portland, Oregon.

McCaffrey, R., A. I. Qamar, R. W. King, R. Wells, G. Khazaradze, C. A. Williams, C. W. Stevens, J. J. Vollick, and P. C. Zwick. 2007. Fault locking, block rotation and crustal deformation in the Pacific Northwest. Geophysical Journal International 169(3):1315–1340.

McFarland, C. R. 1983 Oil and gas exploration in Washington, 1900–1982. Information Circular 75. Department of Natural Resources, Olympia, Washington. http://www.dnr.wa.gov/Publications/ger_ic75_oil_gas_exploration.pdf (accessed 29 July 2018).

Melillo, J. M., T. C. Richmond, and G. W. Yohe, editors. 2014. Highlights of climate change impacts in the United States: the third national climate assessment. U.S. Global Change Research Program. http://nca2014.globalchange.gov/ (accessed 19 July 2017).

Mickelson, K. A., and S. L. Slaughter. 2017. Washington state's new landslide inventory mapping protocol. GSA Annual Meeting poster presentation. Washington State Department of Natural Resources, Olympia, Washington. https://www.dnr.wa.gov/publications/ger_presentations_gsa_2017_mickelson.pdf (accessed 5 September 2017).

Monahan, W. B., and N. A. Fisichelli. 2014. Climate exposure of US National Parks in a new era of change. http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0101302 (accessed 20 July 2017).

Mote, P., A. K. Snover, S. Capalbo, S. D. Eigenbrode, P. Glick, J. Littell, R. Raymondi, and S. Reeder. 2014. Chapter 21 Northwest. Climate change impacts in the United States: The Third National Climate Assessment. Pages 487-513 *in* J. M. Melillo, T. C. Richmond, and G. W. Yohe, editors. US Global Change Research Program. Washington, DC. https://nca2014.globalchange.gov/report/regions/northwest (accessed 3 September 2018).

Moulton, G. E. 1987. The Journals of the Lewis and Clark Expedition. University of Nebraska Press, Lincoln, Nebraska.

National Research Council. 2012. Sea-level rise for the coasts of California, Oregon, and Washington: past, present, and future. The National Academies Press, Washington, DC. https://doi.org/10.17226/13389 (accessed 3 September 2018).

National Weather Service. 2018. Monthly Weather Summary (CLM) for Astoria, November 2018. National Weather Service, Portland Weather Forecast Office, Portland, OR. https://w2.weather.gov/climate/index.php?wfo=pqr (accessed 9 September 2019)

Nelson, A. R., A. E. Jennings, and K. Kashima. 1996. An earthquake history derived from stratigraphic and microfossil evidence of relative sea-level change at Coos Bay, southern coastal Oregon. Geological Society of America Bulletin 108:141–154.

Niem, A.R., and Niem, W.A. 1985. Geologic Map of the Astoria Basin, Clatsop and northwestern most Tillamook Counties, Northwest Oregon (scale 1:100,000). Oil and Gas Investigation 14. Oregon Department of Geology and Mineral Industries, Portland, Oregon. http://www.oregongeology.org/pubs/ogi/OGI-14.pdf (accessed 25 July 2017).

Niem, A. R., W. A. Niem, M. W. Martin, M. M. Kadri, and D. R. McKeel. 1985. Correlation of exploration wells, Astoria Basin, N.W. Oregon: Explanatory text for Plate 2. Oil and Gas Investigation 14, Oregon Department of Geology and Mineral Industries, Portland, Oregon. http://www.oregongeology.org/pubs/ogi/OGI-14.pdf (accessed 25 July 2017).

Niem, A. R., and T. Horning. 2006. Geology of the Columbia River basalts at the Miocene shoreline to the deep sea, NW Oregon. Northwest Geological Society, Seattle, Washington.

NOAA. 2017a. Climate change issue profile: sea level rise. National Oceanic and Atmospheric Administration, Washington, DC. https://www.nps.gov/subjects/climatechange/upload/sea-level-rise-brief-noaa-mpa.pdf (accessed 20 July 2017).

NOAA. 2017b. Tides and currents: Sea level trends. National Oceanic and Atmospheric Administration Center for Operational Oceanographic Products and Services, Silver Spring, Maryland. https://tidesandcurrents.noaa.gov/sltrends/sltrends.html (accessed 20 July 2017).

NPS. 2014. Recent climate change exposure of Lewis and Clark National Historical Park. Climate Change Resource Brief, National Park Service, Washington, DC. https://irma.nps.gov/DataStore/Reference/Profile/2213453 (accessed 9 September 2019).

NPS. 2015. Foundation document: Lewis and Clark National Historical Park, Oregon. LEWI 405/127957. National Park Service, Pacific West Region, Seattle, Washington.

Olmstead, D. L., and M. P. Alger. 1985. Mist gas field: exploration and development 1979-1984. Oil and Gas Investigation 10. Oregon Department of Geology and Mineral Industries, Portland, Oregon. http://www.oregongeology.org/pubs/ogi/OGI-10.pdf (accessed 21 July 2017).

Oregon Climate Change Research Institute. 2012. Water and climate in the Pacific Northwest. Institute for Water and Watersheds, Oregon State University, Corvallis, Oregon.http://water.oregonstate.edu/sites/default/files/water_and_climate_in_the_pacific_northwest_v3.pdf (accessed 7 May 2019).

Oregon Department of Geology and Mineral Industries. 2008. Landslide hazards in Oregon. Fact Sheet. Oregon Department of Geology and Mineral Industries, Portland, Oregon. http://www.oregongeology.org/pubs/fs/landslide-factsheet.pdf (accessed 18 August 2018).

Pacific Northwest Seismic Network. 2017. Plate tectonics. https://pnsn.org/outreach/about-earthquakes/plate-tectonics (accessed 3 July 2017).

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.

Palmer, S. P., S. L. Magsino, E. L. Bilderback, J. L. Poelstra, D. S. Folger, and R. A. Niggemann. 2004. Liquefaction susceptibility map of Pacific County, Washington. Open Fire Report 2004–20. Washington Division of Geology and Earth Resources, Olympia, Washington. ftp://ww4.dnr.wa.gov/geology/pubs/ofr04-20/ofr2004-20_sheet49_pacific_liq.pdf (accessed 24 August 2018).

Pemberton, S. G., J. A. MacEachern, and R. W. Frey. 1992. Trace fossil facies models: environmental and allostratigraphic significance. Pages 47–73 *in* R. G. Walker and N. P. James, editors. Facies models: response to sea level change. Geological Association of Canada, St. John's, Newfoundland, Canada.

Peterson, C. D., E. Stock, D. M. Price, R. Hart, F. Reckendorf, J. M. Erlandson, and S. W. Hostetler. 2007. Ages, distributions, and origins of upland coastal dune sheets in Oregon, USA. Geomorphology 91:80–102.

Reidel, S. P., and T. Tolan. 2013. The Grand Ronde Basalt. Geological Society of America Special Paper 497:117–154. https://www.researchgate.net/publication/268981772_The_Grande_Ronde_Basalt (accessed 7 May 2019).

Retallack, G. J., D. G. Gavin, E. B. Davis, N. D. Sheldon, J. M. Erlandson, M. H. Reed, E. A. Bestland, J. J. Roering, R. J. Carson, and R. B. Mitchell. 2016. Oregon 2100: projected climatic and ecological changes. Bulletin of the Museum of Natural History 26. University of Oregon, Eugene, Oregon.

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, NPS, Washington, DC. https://www.nps.gov/subjects/climatechange/culturalresourcesstrategy.htm (accessed 11 April 2017).

Ronda, J. P. 1984. Lewis and Clark among the Indians. University of Nebraska Press, Lincoln, Nebraska. https://lewisandclarkjournals.unl.edu/item/lc.sup.ronda.01.07 (accessed 23 June 2017).

Santucci, V. L., J. P. Kenworthy, and A. L. Mims. 2009. Monitoring in situ paleontological resources. Pages 189–204 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring (accessed 27 July 2017).

Shugar, D. H., I. J. Walker, O. B. Lian, J. B. R. Eamer, C. Neudorf, D. McLaren, and D. Fedje. 2014. Post-glacial sea-level change along the Pacific coast of North America. Quaternary Science Reviews 97:170–192. http://www.sciencedirect.com/science/article/pii/S0277379114002030 (accessed 1 August 2017).

Smith, J. G., J. Dehn, R. P. Hoblitt, R. G. LaHusen, J. B. Lowenstern, S. C. Moran, L. McClelland, K. A. McGee, M. Nathenson, P. G. Okubo, J. S. Pallister, M. P. Poland, J. A. Power, D. J. Schneider, and T. W. Sisson. 2009. Volcano monitoring. Pages 273–305 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring (accessed 27 July 2017).

Stovall, W. K., A. M. Wilkins, C. W. Mandeville, and C. L. Driedger. 2016. U.S. Geological Survey Volcano Hazards Program: assess, forecast, prepare, engage. Fact Sheet 2016–3040. US Geological Survey, Reston, Virginia. https://pubs.usgs.gov/fs/2016/3040/fs20163040.pdf (accessed 19 August 2019).

Sweet, W. V., R. Horton, R. E. Kopp, A. N. LeGrande, and A. Romanou. 2017. Sea level rise. Pages 333–363 *in* D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock, editors. Climate Science Special Report: Fourth National Climate Assessment, Volume I. U.S. Global Change Research Program, Washington, DC. https://science2017.globalchange.gov/chapter/12/ (accessed 27 August 2018).

Tissot, B. P., and D. H. Welte. 1978. Petroleum formation and occurrence. Springer-Verlag, New York, New York.

Tolan, T. L., S. P. Reidel, M. H. Beeson, J. L. Anderson, K. R. Fecht, and D. A. Swanson. 1989. Revisions to the estimates of the areal extent and volume of the Columbia River Basalt Group. Pages 1–20 *in* S. P. Reidel and P. R. Hooper, editors. Volcanism and tectonism in the Columbia River Flood-Basalt Province. Special Paper 239. Geological Society of America, Boulder, Colorado.

Toomey, R. S., III. 2009. Geological monitoring of caves and associated landscapes. Pages 27–46 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring (accessed 27 July 2017).

USGS. 2002. Columbia Plateau, Columbia River Basin, Columbia River flood basalts. USGS Volcano Hazards Program. https://volcanoes.usgs.gov/observatories/cvo/cvo_columbia_river_basalt.html (accessed 22 November 2016).

Vano, J. A., B. Nijssen, and D. P. Lettenmaier. 2015. Seasonal hydrologic responses to climate change in the Pacific Northwest. Water Resources Research 51:1959–1976.

Vose, R. S., D. R. Easterling, K. E. Kunkel, A. N. LeGrande, and M. F. Wehner. 2017. Temperature changes in the United States. Pages 185–206 *in* D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock, editors. Climate Science Special Report: Fourth National Climate Assessment, Volume I. US Global Change Research Program, Washington, DC. https://science2017.globalchange.gov/chapter/6/ (accessed 27 August 2018).

Walker, R. G. 1992. Turbidites and submarine fans. Pages 239–265 *in* R. G. Walker and N. P. James, editors. Facies models: response to sea level change. Geological Association of Canada, St. John's, Newfoundland, Canada.

Walsh T. J., C. G. Caruthers, A. C. Heinitz, E. P. Myers III, A. M. Baptista, G. B. Erdakos, and R. A. Kamphaus. 2000. Tsunami hazard map of the southern Washington coast: modeled tsunami inundation from a Cascadia Subduction Zone earthquake. Geologic Map GM–49 and brochure. Washington Division of Geology and Earth Resources, Olympia, Washington. http://www.dnr.wa.gov/geology/ (accessed 13 August 2018).

Washington Geological Survey. 2017a. What are landslides? Washington Geological Survey, Olympia, Washington. https://www.dnr.wa.gov/publications/ger_fs_landslide_processes.pdf?xz1gdq (accessed 20 August 2018).

Washington Geological Survey. 2017b. Landslide hazards in Washington state. Washington Geological Survey, Olympia, Washington. https://www.dnr.wa.gov/publications/ger_fs_landslide_hazards.pdf?wimsdt (accessed 20 August 2018).

Wells, R. E. 1989. Geologic map of the Cape Disappointment–Naselle River area, Pacific and Wahkiakum Counties, Washington (scale 1:62,500). Miscellaneous Investigations Series Map I–1832. U S Geological Survey, Reston, Virginia. https://ngmdb.usgs.gov/Prodesc/proddesc_9948.htm (accessed 20 August 2018).

Wells, R. E., A. R. Niem, R. C. Evarts, and J. T. Hagstrum. 2009. The Columbia River Basalt Group—from the gorge to the sea. Pages 737–774 *in* J. E. O'Connor, R. J. Dorsey, and I. P. Madin, editors. Volcanoes to vineyards: Geologic field trips through the dynamic landscape of the Pacific Northwest. Geological Society of America Field Guide 15. Geological Society of America, Boulder, Colorado.

Wells, R. E., C. S. Weaver, and R. J. Blakely. 1998. Fore arc migration in Cascadia and its neotectonic significance. Geology 26: 759–762.

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. http://go.nps.gov/geomonitoring (accessed 27 July 2017).

Wong, P. P., I. J. Losada, J.-P. Gattuso, J. Hinkel, A. Khattabi, K. L. McInnes, Y. Saito, and A. Sallenger. 2014. Coastal systems and low-lying areas. Pages 361–409 *in* C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, and L. L.White, editors. Climate change 2014: impacts, adaptation, and vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, New York. http://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap5_FINAL.pdf (accessed 27 August 2018).

Young, R. and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring (accessed 26 July 2017).

Additional References

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

Geology of National Park Service Areas

- NPS Geologic Resources Division (Lakewood, Colorado) *Energy and Minerals; Active Processes and Hazards; Geologic Heritage*: http://go.nps.gov/grd
- NPS Geologic Resources Division Education Website: http://go.nps.gov/geoeducation
- NPS Geologic Resources Inventory: http://go.nps.gov/gri
- NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program: http://go.nps.gov/gip

NPS Resource Management Guidance and Documents

- Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html
- 1998 National parks omnibus management act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf
- NPS-75: Natural resource inventory and monitoring guideline: https://irma.nps.gov/DataStore/Reference/Profile/622933
- NPS Natural resource management reference manual #77: https://irma.nps.gov/DataStore/Reference/Profile/572379
- Geologic monitoring manual (Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado): http://go.nps.gov/geomonitoring
- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): https://www.nps.gov/dsc/technicalinfocenter.htm

Climate Change Resources

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

Geological Surveys and Societies

- Oregon Department of Geology and Mineral Industries: http://www.oregongeology.org/sub/default.htm
- Washington State Department of Natural Resources: Geology and Earth Resources: http://www.dnr.wa.gov/geology
- US Geological Survey: http://www.usgs.gov/
- Geological Society of America: http://www.geosociety.org/
- American Geophysical Union: http://sites.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: http://www.stategeologists.org/

US Geological Survey Reference Tools

- National geologic map database (NGMDB): http://ngmdb.usgs.gov/ngmdb/ngmdb_home.html
- Geologic names lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/search
- Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/
- GeoPDFs (download PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")
- Publications warehouse (many publications available online): http://pubs.er.usgs.gov
- Tapestry of time and terrain (descriptions of physiographic provinces): http://pubs.usgs.gov/imap/i2720/

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting, held on 14 October 2009. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://go.nps.gov/gripubs.

2009 Scoping Meeting Participants

Name	Affiliation	Position
Bolitho, Zack	NPS Lewis and Clark NHP	Chief, Resource Management
Cole, Carla	NPS Lewis and Clark NHP	Natural Resource Project Manager
Davis, Marsha	NPS Pacific West Regional Office	Geologist
Eid, Nancy	NPS Lewis and Clark NHP	Biologist
Graham, John	Colorado State University	Geologist, GRI Report Writer
Heise, Bruce	NPS Geological Resources Division	Geologist, GRI Program Coordinator (retired)
Horning, Tom	Horning Geosciences	Geologist, Owner
Mack, Gregory	NPS Pacific West Regional Office	Geologist, GIS Specialist (retired)
Madin, Ian	Oregon Department of Geology and Mineral Industries	Chief Scientist
Stokeld, Rachel	NPS Lewis and Clark NHP	Museum Technician
Wood, Deborah	NPS Lewis and Clark NHP	Cultural Resource Program Manager

Appendix B: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to NPS minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of December 2018. Contact the NPS Geologic Resources Division for detailed guidance

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester. **National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of cave and karst resources. **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be 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.
Paleontology	**National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa et seq.** provides for the management and protection of paleontological resources on federal lands.	**36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted. **43 CFR Part 49** (in development) will contain the DOI regulations implementing the Paleontological Resources Preservation Act.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
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.
Geothermal	**Geothermal Steam Act of 1970, 30 USC. § 1001 et seq. as amended in 1988**, states ● No geothermal leasing is allowed in parks. ● "Significant" thermal features exist in 16 park units (the features listed by the NPS at **52 Fed. Reg. 28793-28800** (August 3, 1987), plus the thermal features in Crater Lake, Big Bend, and Lake Mead). ● NPS is required to monitor those features. ● Based on scientific evidence, Secretary of Interior must protect significant NPS thermal features from leasing effects. **Geothermal Steam Act Amendments of 1988, Public Law 100--443** prohibits geothermal leasing in the Island Park known geothermal resource area near Yellowstone and outside 16 designated NPS units if subsequent geothermal development would significantly adversely affect identified thermal features.	None applicable.	**Section 4.8.2.3** requires NPS to ● Preserve/maintain integrity of all thermal resources in parks. ● Work closely with outside agencies. ● Monitor significant thermal features.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Mining Claims (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.

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

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

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

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Climate Change	**Secretarial Order 3289** (Addressing the Impacts of Climate Change on America's Water, Land, and Other Natural and Cultural Resources) (2009) requires DOI bureaus and offices to incorporate climate change impacts into long-range planning; and establishes DOI regional climate change response centers and Landscape Conservation Cooperatives to better integrate science and management to address climate change and other landscape scale issues. **Executive Order 13693** (Planning for Federal Sustainability in the Next Decade) (2015) established to maintain Federal leadership in sustainability and greenhouse gas emission reductions.	*No applicable regulations, although the following NPS guidance should be considered:* **Coastal Adaptation Strategies Handbook (Beavers et al. 2016)** provides strategies and decision-making frameworks to support adaptation of natural and cultural resources to climate change. **Climate Change Facility Adaptation Planning and Implementation Framework**: The NPS Sustainable Operations and Climate Change Branch is developing a plan to incorporate vulnerability to climate change (Beavers et al. 2016b). **NPS Climate Change Response Strategy** (2010) describes goals and objectives to guide NPS actions under four integrated components: science, adaptation, mitigation, and communication. **Policy Memo 12-02** (Applying National Park Service Management Policies in the Context of Climate Change) (2012) applies considerations of climate change to the impairment prohibition and to maintaining "natural conditions". **Policy Memo 14-02** (Climate Change and Stewardship of Cultural Resources) (2014) provides guidance and direction regarding the stewardship of cultural resources in relation to climate change. **Policy Memo 15-01** (Climate Change and Natural Hazards for Facilities) (2015) provides guidance on the design of facilities to incorporate impacts of climate change adaptation and natural hazards when making decisions in national parks. *Continued in 2006 Management Policies column*	**Section 4.1** requires NPS to investigate the possibility to restore natural ecosystem functioning that has been disrupted by past or ongoing human activities. This would include climate change, as put forth by Beavers et al. (2016). *NPS guidance, continued:* **DOI Manual Part 523, Chapter 1** establishes policy and provides guidance for addressing climate change impacts upon the Department's mission, programs, operations, and personnel. **Revisiting Leopold: Resource Stewardship in the National Parks** (2012) will guide US National Park natural and cultural resource management into a second century of continuous change, including climate change. **Climate Change Action Plan** (2012) articulates a set of high-priority no-regrets actions the NPS will undertake over the next few years **Green Parks Plan** (2013) is a long-term strategic plan for sustainable management of NPS operations.

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

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Soils	**Soil and Water Resources Conservation Act, 16 USC §§ 2011–2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources. **Farmland Protection Policy Act, 7 USC § 4201 et. seq.** requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).	**7 CFR Parts 610 and 611** are the US Department of Agriculture regulations for the Natural Resources Conservation Service. **Part 610** governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. **Part 611** governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements.	**Section 4.8.2.4** requires NPS to ● prevent unnatural erosion, removal, and contamination; ● conduct soil surveys; ● minimize unavoidable excavation; and ● develop/follow written prescriptions (instructions).

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