National Park Service
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Natural Resource Stewardship and Science

Fort Vancouver National Historic Site

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2019/1887





ON THE COVER
The bastion at Fort Vancouver National Historic Site. Photograph by Christopher Communications and provided by Meagan Huff, Fort Vancouver National Historic Site.

THIS PAGE
McLoughlin House
National Park Service photograph available at https://www.nps.gov/fova/learn/historyculture/mcloughlin-house.htm

Fort Vancouver National Historic Site

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2019/1887

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March 2019

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

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Please cite this publication as:

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.

NPS 389/150823, March 2019

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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 over 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 Fort Vancouver National Historic Site, 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.

The 84 ha (207 ac) of Fort Vancouver National Historic Site preserves a small portion of a unique geologic landscape that supported a widely divergent cultural milieu that included American Indians, Europeans, and Pacific Islanders. Complex tectonic plate collisions that pulled apart the Portland Basin, volcanic activity that produced voluminous basaltic lava flows, and colossal ice age floods carved a landscape like none other on Earth. The broad floodplain of the Columbia River became a focal point for Clackamas, Multnomah, Cascades, Chinooks, Klickitats, Cowlitz, Kalapuyas, and many other American Indian tribes. In 1825, John McLoughlin, the chief executive of Britain's Hudson's Bay Company, constructed Fort Vancouver on an extensive terrace formed by ice age floods. The fur trading fort soon became the cultural, commercial, manufacturing, and political hub of the Pacific Northwest with American Indians interacting with such diverse cultures as French Canadians, English, Native Hawaiians, Scots, and Métis. When the Oregon Territory became part of the United States in 1846, John McLoughlin moved across the river to Oregon City, Oregon, applied for citizenship, and built a house on the east bank of the Willamette River, adjacent to Willamette Falls. In the 20th century, McLoughlin's house, and the house of Dr. Forbes Barclay, the Hudson's Bay Company physician, were relocated to a bluff consisting of basaltic lava flows that overlook Willamette Falls (fig. 1).

In 1849, the US Army established its regional headquarters at Fort Vancouver. The historic site includes the eastern and southern portions of the US Army barracks while the Vancouver National Historic Reserve, a wider area owned and managed by the city of Vancouver, includes the western portion of the Vancouver Barracks and Officer's Row. Local stones were used as building material for the foundation and basement of Officer's Row. The relatively level floodplain of the Columbia River was an ideal site for an airfield, and in 1911, the first airplane landed at Pearson Field. In 1937, Pearson Field became the landing site for the first non-stop transpolar flight.

Authorized as a national monument in 1948 and redesignated as a national historic site in 1961, Fort Vancouver National Historic Site preserves a premier archaeological site, the region's first military post, an international fur trade emporium, a portion of one of the oldest airfields, Pearson Air Museum, the first national historic site west of the Mississippi River, a waterfront trail on the banks of the Columbia River, and a section of the Ice Age Floods National Geologic Trail, which is the nation's first National Geologic Trail. Fort Vancouver National Historic Site includes cultural artifacts documenting over 200 years of diverse, multicultural communities in the region and geologic features that document about 20 million years of geologic processes that formed the present landscape.

Geologic features and processes within Fort Vancouver National Historic Site, adjacent Vancouver National Historic Reserve, and the surrounding region include:

- **Fluvial features**. In the Fort Vancouver unit, coarsening upward sequences record aggradation (backfilling) due to sea level rise and abundant sediment supply. Boulders deposited on extensive gravel beds document ice age flooding. Overbank flooding of the Columbia River resulted in a relatively flat area. Willamette Falls, which can be seen from the McLoughlin unit, preserves evidence of voluminous basalt flows, catastrophic ice age flooding, and regional faulting.
- **Glacial features**. Erosional and depositional features resulting from outburst floods from glacial Lake Missoula occur in the region and include the terrace upon which Officer's Row rests.

- **Lacustrine features**. Remnants of a lake that was used as a trash deposit for Fort Vancouver has provided a wealth of archeological artifacts.
- **Paleontological resources**. The archeology collection includes fossil bones, shells, and teeth in association with other artifacts.
- **Basalt flow features**. Boring Volcanic Field lava flows, which cap the Oregon City Plateau, and the Columbia River Basalt Group upon which the McLoughlin and Barclay houses were built record episodes of volcanic activity.
- **Alpine glacial features**. Rock debris from alpine glaciers formed large outwash terraces that once impeded the flow of the Columbia River.
- **Dunes**. East–west trending sand dunes north of the historic site have been interpreted as resulting from either strong easterly winds blowing through the Columbia Gorge or as forming beneath the surface of glacial Lake Missoula floodwaters channeled through Lacamas Lake trough.
- **Coastal features**. Tidal influence from the Pacific Ocean reaches Bonneville Dam, east of Fort Vancouver.
- **Willamette Falls**. The waterfall in the Willamette River plunges over the Columbia River Basalt Group, and is linked to John McLoughlin and the McLoughlin House unit. Movement on the Bolton Fault may have initiated the falls.
- **Faults**. The Portland Hills, Oatfield, and Bolton faults cut the Portland Hills anticline between the Fort Vancouver and McLoughlin House units.
- **Slope movements**. Rotational slumps and slide masses, often triggered by earthquakes, are mapped near the McLoughlin House unit.
- **Volcanic features**. Thick basalt flows and cinder cones from volcanic activity millions of years ago form much of the landscape on the Oregon City Plateau, upon which the McLoughlin House unit is located.
- **Global climate change features**. As sea level rises, the Columbia River aggrades with sediment. Features associated with the river bank adjacent to the Fort Vancouver may change due to erosion caused by heightened tidal fluctuations.

Geologic resource management issues that may directly impact the historic site include the following:

- **Flooding**. Overbank flooding or groundwater seepage may inundate portions of the Fort Vancouver unit.
- **Inventory, monitoring, and protection of paleontological resources.** Fossils discovered in alluvium and artificial fill are maintained in the park's archeology collections. Some of the fossils may be from personal collections. Recommendations for future archeology excavations include an accompanying paleontological survey.
- **Slope movement and infrastructure**. Boulders, remnants of the ice age floods, may interfere with construction and infrastructure maintenance in the Fort Vancouver unit, and cliff collapse may destabilize the foundations of the McLoughlin and Barclay houses in the McLoughlin unit.
- **Radon exposure**. Granitic rocks in the terrace gravels used in the construction of the foundation and basements of Officer's Row contain radon, the colorless, odorless, heavier-than-air radioactive gas that is the natural decay product of Uranium. Long term exposure to elevated levels of radon increases the risk of lung cancer.
- **Earthquakes**. Although the probability of the Fort Vancouver area being shaken by a magnitude 6 earthquake is less than 0.20 and the probability of a magnitude 7 earthquake is less than 0.02, earthquakes in the past have triggered landslides. Earthquakes in the region may signal the reactivation of old faults and subsequent movement parallel to the fault plane. No faults have been mapped in Fort Vancouver National Historic Site, but unidentified faults may be present in the subsurface. The Bolton Fault has been mapped about 300 m (1,000 ft) from the McLoughlin House. A major earthquake along the Cascadia Subduction Zone will affect much of the Pacific Northwest, including Fort Vancouver National Historic Site.
- **Global climate change**. Long-term impacts will include changes to the river and groundwater levels, increased aggradation in the Columbia River from sea level rise, and increased slumping and erosion from an increase in precipitation, which may directly impact the McLoughlin House unit.

Geologic processes that may generate geologic issues for resource managers on a regional scale include:

- **Fault movement**. Although movement on regional faults has been ongoing since the middle Miocene, slip rates are very low and recurrence intervals are on the order of tens of thousands of years, suggesting minimal potential hazards.
- **Earthquakes**. Local earthquake events and movement caused by the offshore Cascadia Subduction Zone pose threats of shaking and liquefaction that might damage the infrastructure in the low-lying areas in the Fort Vancouver unit. The Pacific Northwest Seismic Network (PNSN) continuously monitors seismic activity (earthquakes) in the Pacific Northwest.

- **Slope movement (landslides).** Intense rainfall events may trigger landslides that may destabilize the bluff behind the McLoughlin and Barclay houses and damage the McLoughlin House unit.
- **Volcanic activity**. Cinder cones in the Portland area are part of the Boring Volcanic Field, but all of the existing volcanic centers of the Boring Volcanic Field are extinct, although the field may not be. Currently, most of the volcanic activity occurs in the Cascade Range to the east of the historic site. Volcanic activity is continuously monitored by the USGS Cascades Volcano Observatory (CVO). According to the CVO, the probability of an eruption in the Portland/ Vancouver metro area is very low.
- **Issues associated with global climate change**. Rising sea level and an increase in rainfall frequency and intensity may lead to increased flooding, shallow groundwater, and slumping.

The geology of Fort Vancouver National Historic Site documents roughly 20 million years of Earth history. Deposits in the park and throughout the region capture four main geologic episodes: (1) the development of the Portland Basin, (2) the eruption of vast quantities of basalt, (3) the evolution of the Columbia River, and (4) the influence of catastrophic ice age floods on the current landscape.

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 two GRI-compiled geologic maps of Fort Vancouver National Historic Site. The map covering the Fort Vancouver unit was compiled as part of a GRI-supported mapping effort. The map covering the McLoughlin unit was originally published by the Oregon Department of Geology and Mineral Industries (DOGAMI).

Products and Acknowledgments

The NPS Geologic Resources Division partners with the Colorado State University Department of Geosciences to produce GRI products. The Oregon Department of Geology and Mineral Industries and a graduate student working with the United States Geological Survey developed the source maps. This chapter describes GRI products and acknowledges contributors to this report.

GRI Products

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

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

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

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

Acknowledgments

Mapping of the Fort Vancouver unit was partially funded by the GRI program.

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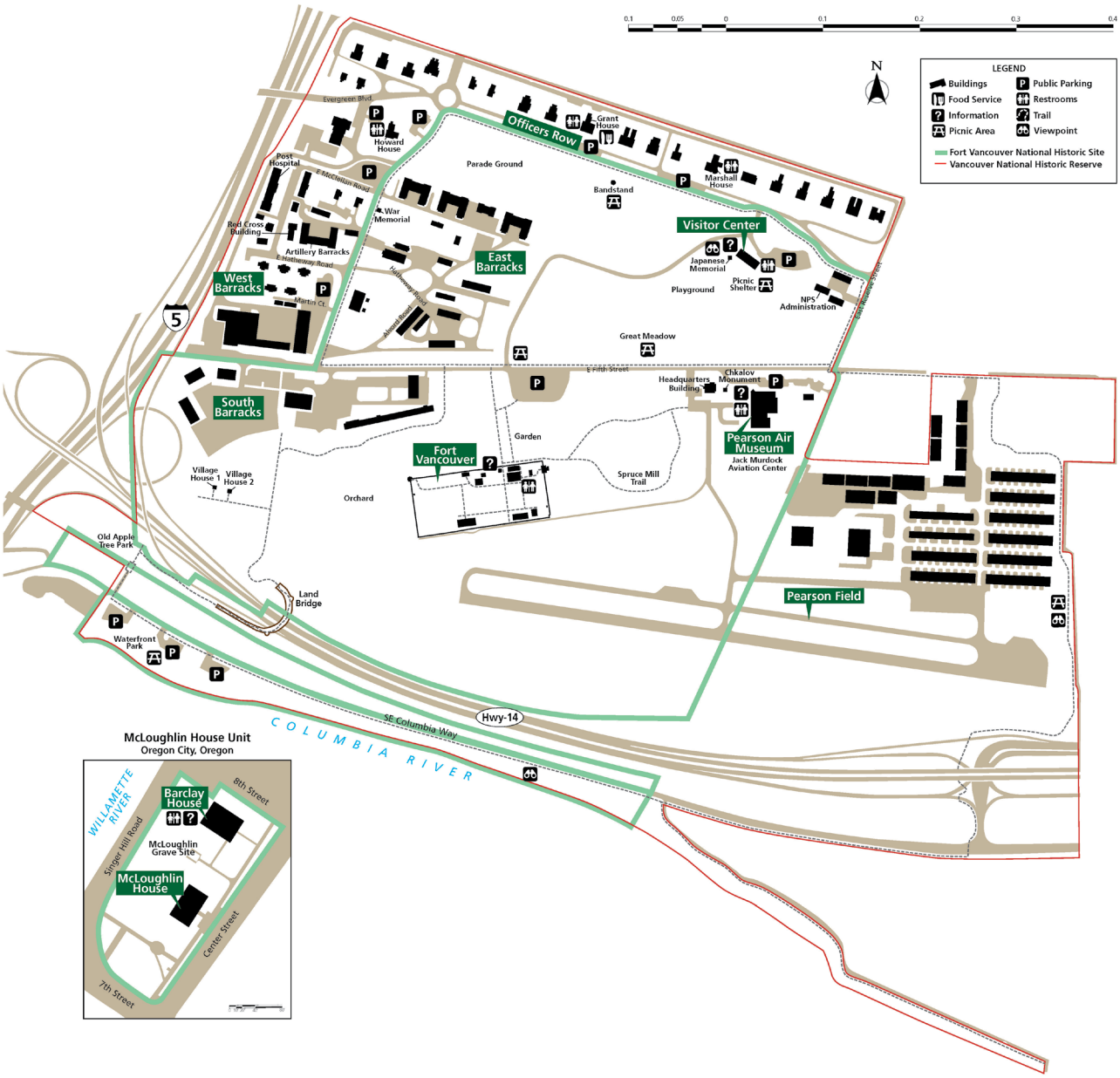


Figure 1. Map of the Fort Vancouver National Historic Site.
The Fort Vancouver unit (upper map) lies north of the Columbia River. The McLoughlin House unit (lower map) is located on Singer Hill, adjacent to Willamette Falls and south of the Columbia River. NPS map.

Geologic Setting and Significance

This chapter describes the regional geologic setting of Fort Vancouver National Historic Site and summarizes connections among geologic resources, other park resources, and park stories.

Park Establishment and Significance

Fort Vancouver National Historic Site (fig. 1) preserves part of the Portland Basin, a globally unique landscape resulting from extraordinary earth processes including plate tectonic collisions, intense volcanic activity that produced voluminous flood basalts, catastrophic ice age flood events, and an evolving Columbia River system. The juncture of such widely divergent geologic processes as plate tectonic collision, volcanism, and Pleistocene Ice Age floods carved the foundation of Fort Vancouver National Historic Site. In addition to the exceptional landscape, Fort Vancouver may have no equal in the National Park Service (NPS) with regards to the plethora of widely dissimilar and diverse cultures and communities that once interacted with each other. Clackamas, Multnomah, Cascades, Chinooks, Klickitats, Cowlitz, Kalapuyas, and many other American Indian tribes gathered on these 84 ha (207 ac) along the northern bank of the Columbia River to share harvests and trade goods. Once Fort Vancouver was established, the cultural milieu at the fort not only included American Indians, French Canadians, and English but also such diverse cultures as Native Hawaiians, Scots, and Métis, which have both American Indian and European ancestry. This mix of cultures is considered a primary interpretive theme of the park (NPS 2017).

Under the stewardship of Dr. John McLoughlin, the chief executive of Britain's Hudson's Bay Company, Fort Vancouver became the center of political, cultural, commercial, and manufacturing activities from 1825 to 1846. With the passage of the 1846 Oregon Treaty, which established the 49th parallel as the border between the United States and British North America (except for Vancouver Island), the Hudson's Bay Company abandoned Fort Vancouver. In 1849, the US Army established its regional headquarters in what is today Fort Vancouver National Historic Site, using local stone as building material for the foundation and basement of Officer's Row. The barracks are separate from Britain's fur trading fort, and the eastern and southern portions are part of the historic site. In addition to barracks, Fort Vancouver maintained the world's largest sawmill at the time, which provided lumber for aircraft during World War I. The US Army also established Pearson Field on the level floodplain of the Columbia River (fig. 1). The first airplane landed in 191l, and in 1937 Pearson Field became the landing site for the first transpolar flight. The fort also became the regional headquarters for the Civilian Conservation Corps. In 2011, the US Army ceased its operations at Fort Vancouver, and in 2012, it relinquished ownership of the property to the NPS (NPS 2017).

Fort Vancouver National Historic Site is distinct from the Vancouver National Historic Reserve. The Reserve is a wider area and includes the western portion of Vancouver Barracks and Officer's Row. These are owned and managed by the City of Vancouver (fig. 1).

Authorized as a national monument in 1948 and changed to a national historic site in 1961, Fort Vancouver National Historic Site also includes the McLoughlin and Barclay houses located approximately 30 km (20 mi) south of Fort Vancouver in Oregon City, Oregon (fig. 2). After the Oregon Treaty was passed, Dr. John McLoughlin moved to Oregon City and applied for American citizenship, as did Dr. Forbes Barclay, the Hudson's Bay Company physician. McLoughlin and Barclay built houses on the east bank of the Willamette River near Willamette Falls. Both men served terms as the mayor of Oregon City. Taking advantage of the river and the falls and surrounding agricultural area, McLoughlin owned sawmills, a gristmill, a granary, and a shipping company (NPS 2016). He donated land for schools and churches. McLoughlin is commonly referred to as "the Father of Oregon" because of the assistance he provided to migrating American homesteaders. In addition to being the town's physician, Barclay became the first official coroner in Oregon and served as superintendent of schools.

The McLoughlin Memorial Association rescued McLoughlin's house from being demolished, and in 1909, the house was moved to its present location on Singer Hill. The Barclay house remained in the Barclay family until the 1930s when it, too, was relocated to Singer Hill adjacent to the McLoughlin House. In 2003, the McLoughlin House National Historic Site, which included the McLoughlin and Barclay houses, became a unit of Fort Vancouver National Historic Site (NPS 2017).

Fort Vancouver National Historic Site joins together a premier archaeological site, the region's first military post, an international fur trade emporium, a portion of the oldest airfield in the Pacific Northwest, the Pearson Air Museum, the first national historic site west of the Mississippi River, a waterfront trail on the banks of the Columbia River, and a segment of the Ice Age NationalGeologic Trail. Archeological sites at Fort Vancouver record over 200 years of history involving





Figure 2. Photographs of the McLoughlin (A) and Barclay (B) houses, Fort Vancouver National Historic Site. NPS photographs.

the extensive interaction of diverse, multicultural communities. The purpose of the park aims to preserve and interpret these historical resources and promote public understanding and appreciation for the multilayered history captured by Fort Vancouver (NPS 2017). By preserving this cultural footprint, the park also preserves a geological heritage unique to the Pacific Northwest.

Geologic Setting

Fort Vancouver National Historic Site lies within the Portland Basin (fig. 3), one of several depressions that collectively comprise the Puget-Willamette forearc, defined as that region of the Cascadia Subduction Zone between the oceanic trench and the Cascade Range volcanoes (fig. 4). The rhomboid-shaped Portland Basin began forming roughly 20 million years ago, during the early Miocene (fig. 5). Oblique convergence of the Pacific Plate beneath the North American Plate resulted in the clockwise rotation of the northward-moving Oregon Coast Range microplate, which caused the Portland Hills to bend upward into an anticline (convex fold) and the adjacent Portland Basin to bow downward into a syncline (concave fold). Bisected by the Columbia River, the Portland Basin occupies a globally exceptional geologic setting wherein a continental-scale river flows through a basin developed within a tectonically-active, convergent-margin (Evarts et al. 2009a).

The base of today's subsiding Portland Basin is about 460 m (1,500 ft) below current sea level, far below today's land surface. The layers of rock and sediment that fill the Portland Basin record a unique blend of aggradation (sediment buildup) and incision in response to tectonic movement that caused earthquakes and subsidence, voluminous flood basalts, regionally and locally derived sediment and volcanic debris, and catastrophic flood deposits (table 1). The 16 million-to15 million-year-old basalt flows of the Columbia River Basalt Group cover roughly 164,000 km^2 (63,000 mi^2) of the Pacific Northwest and are the oldest in situ rocks in Fort Vancouver National Historic Site (Evarts et al. 2009a; Madin 2009). Originating from fissures in the eastern Oregon crust, the basaltic lava flowed into a broad Columbia River Valley and poured into Oregon and Washington. Flows also spread over portions of Idaho, Nevada, and California (fig. 6). Many of the individual flows inundated thousands of square kilometers with volumes up to thousands of cubic kilometers (Tolan et al. 1989). The Grande Ronde Basalt (GIS layers Tgww and Tgsb), which is about 45 m (150 ft) thick, and the 75–90 m- (250–300 ft) thick section of Wanapum Basalt (**Twfg**, **Twfs**) represent the Columbia River Basalt Group in the Fort Vancouver National Historic Site map area (table 1).

River and lake sediments of the Troutdale Formation (**Tt**) eventually buried the Columbia River Basalt Group in the Portland Basin (fig. 7). In the map area, as much as 345 m (1,100 ft) of Troutdale Formation overlies these thick basalt flows (table 1). The isolated hills and hill clusters scattered primarily southeast of Fort Vancouver in the Portland Basin form the Boring Volcanic Field (table 1). Cored by cinder cones and associated lava flows, the hills, some as much as 200 m (600 ft) high, record volcanic activity primarily younger than 1.8 million years ago (Evarts et al. 2009a). The basalt of Canemah (**Tbc**), part of the Boring Volcanic Field Rocks, overlies the Troutdale Formation throughout most of the mapped area (table 1).

Fort Vancouver Unit

Quaternary deposits in the Columbia River Valley of the Portland Basin present a complicated history. The deposits contain evidence of at least four sequences including: (1) an aggrading (backfilling) Pleistocene alluvial plain, (2) a steep valley that incised into the

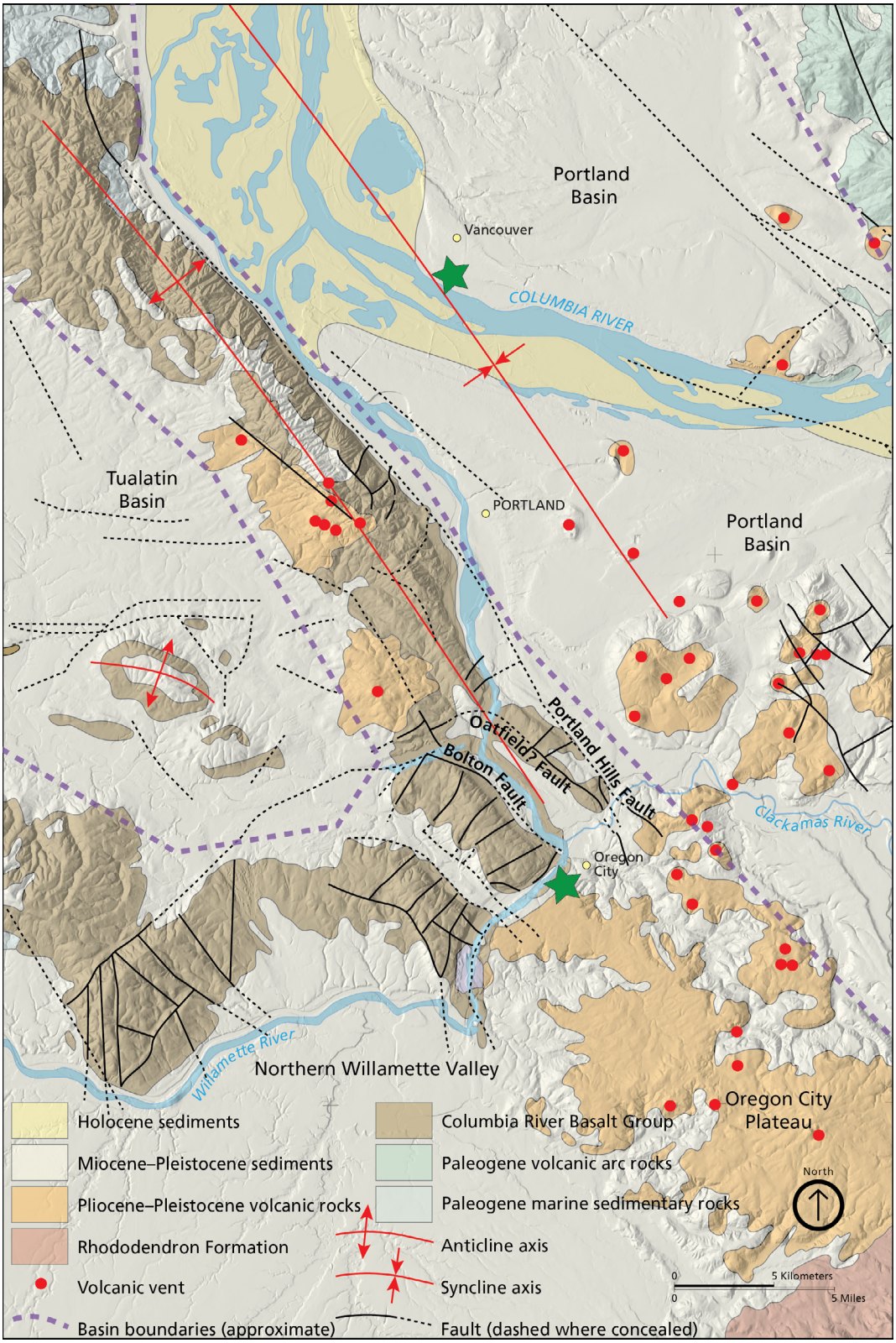


Figure 3. Map of the Portland Basin and Oregon City Plateau.
The rhomboid-shaped Portland Basin resulted from tectonic collision and clockwise rotation of the region. The Oregon City Plateau consists of basaltic lava flows from the Columbia River Basalt Group overlain by sediments of the Troutdale Formation and capped by Boring Volcanic Field lava flows. Green stars indicate location of Fort Vancouver National Historic Site. Diagram by Trista Thornberry-Ehrlich (Colorado State University), modified from Evarts et al. (2009; figure 1).

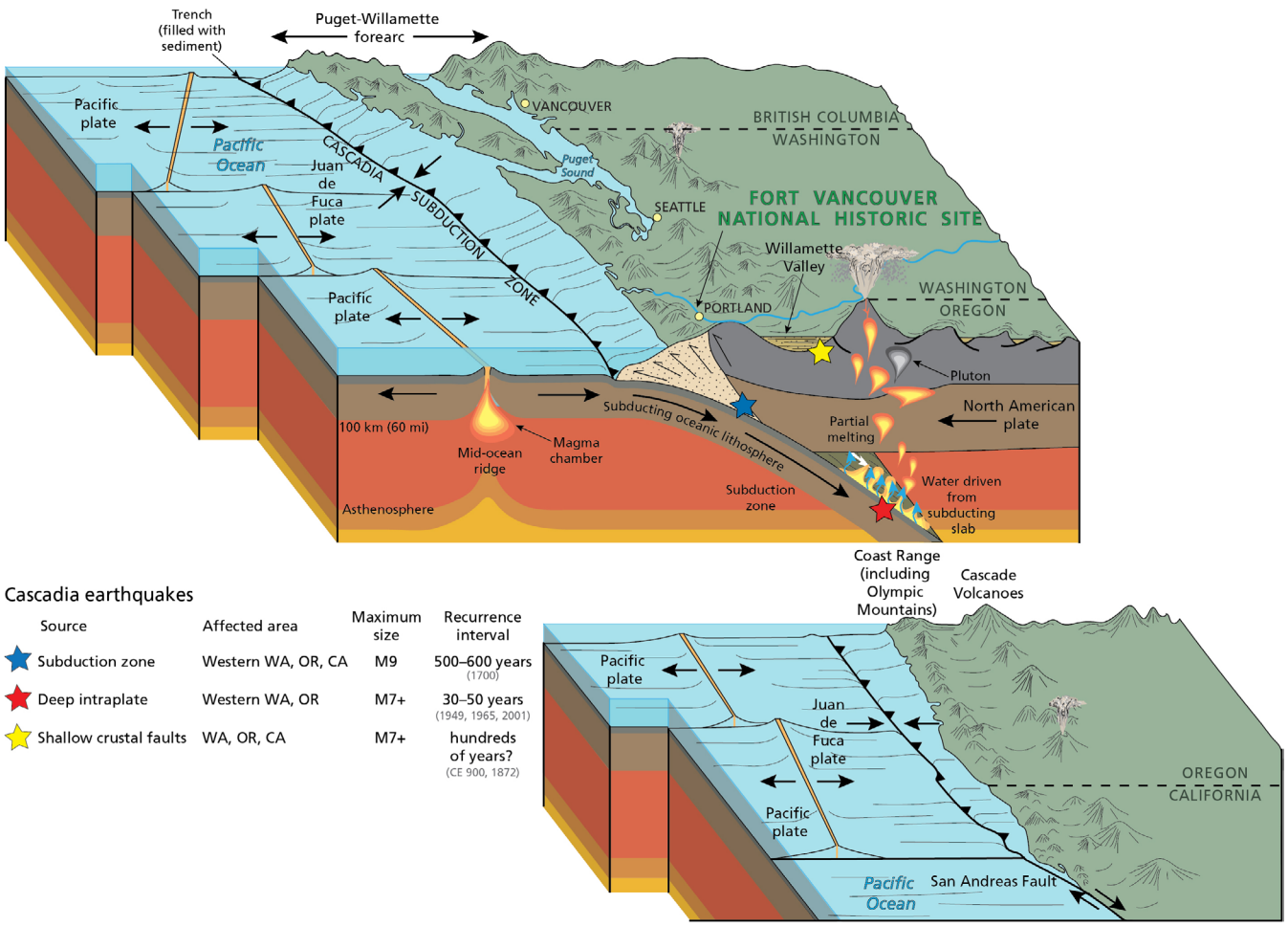


Figure 4. Illustration of the Cascadia Subduction Zone.
Fort Vancouver National Historic Site is located in the gorge bisecting the Cascade Range. At the convergent boundary, the denser Juan de Fuca Plate subducts beneath the North American Plate. Sediment and basalt scraped off the ocean floor becomes accreted to the North American continent. Subduction also causes earthquakes. Note that a deep Juan de Fuca plate earthquake occurred in 2001. Rocks melt to form magma, which rises to the surface to form volcanoes or solidifies to form granitic plutons and batholiths in the subsurface. CE: Common Era (preferred to "AD"). Diagram by Trista Thornberry-Ehrlich (Colorado State University). Cascadia earthquake sources information from the U.S. Geological Survey and Pacific Northwest Seismic Network (http://www.pnsn.org/outreach/earthquakesources; accessed 10 November 2012.

Pleistocene plain, (3) terrace-like features resulting from glacial Lake Missoula outburst floods, and (4) Holocene flooding surfaces (Peterson et al. 2011). Fort Vancouver is dominated by late Pleistocene Missoula flood deposits (**Qff**) and Holocene alluvium deposited in the Columbia River floodplain (**Qac**). During the Pleistocene ice ages, catastrophic floods from glacial Lake Missoula (see "Geologic Significance and Connections") spread cobbles and boulders throughout the Portland Basin (O'Connor et al. 2016). These megaflood bar deposits, beveled to a relatively flat service since the end of the most recent ice age, are commonly referred to as terraces, but this designation may misrepresent the genesis of the deposits (Waitt 2016). As explained by R. Waitt, river terraces form gradually over a long period of time from river processes, whereas the megaflood bar deposits in the Columbia River Valley represent catastrophic processes that occur relatively fast (Richard Waitt, USGS Cascades Volcano Observatory, research geologists, written communication 21 July 2017). The buildings at Fort Vancouver were built on terraces interpreted to be composed of Missoula flood deposits (**Qff**). However, terrace gravels may also represent past alpine glaciers that flowed down the Lewis River from the summit of Mt. Adams and other Cascade Mountains to the north (Evarts et al. 2009a).

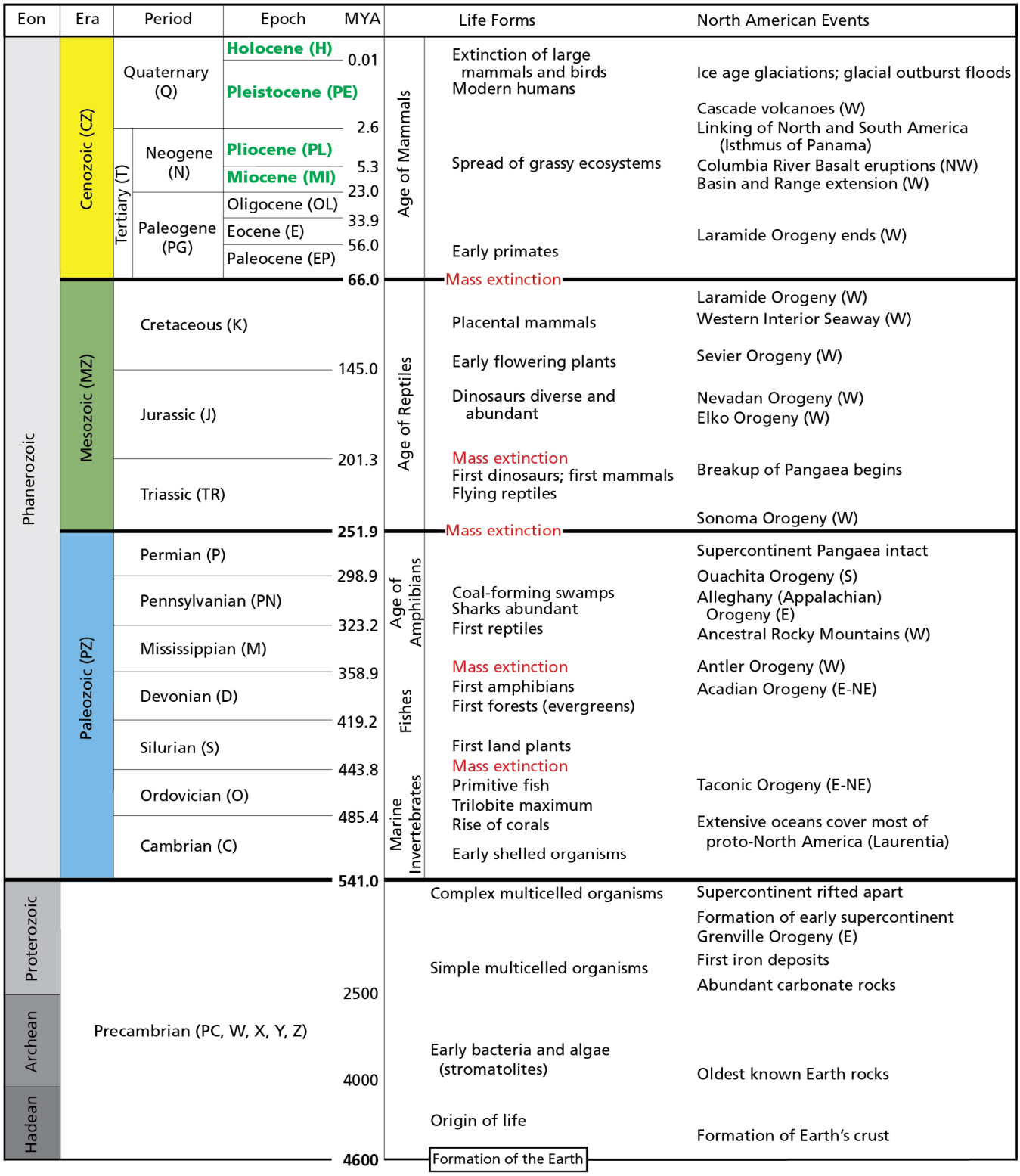


Figure 5. The geologic time scale.
The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. Compass directions in parentheses indicate the regional locations of events. Boundary ages are millions of years ago (MYA). Green text indicates the ages of geologic units that are mapped within Fort Vancouver National Historic Site. NPS graphic using dates from the International Commission on Stratigraphy, available at http://www.stratigraphy.org/index.php/ics-chart-timescale (accessed 7 May 2015).

Table 1. The stratigraphic column for the Fort Vancouver National Historic Site area.

In the description column, "MYA" refers to millions of years ago, and "B.P." refers to years before present. Map unit names in bold type are mapped within Fort Vancouver National Historic Site. In 2009, after the fieldwork was completed for the GRI source map (Madin et al. 2009), the boundary of the Pleistocene was moved from 1.8 to 2.6 MYA; hence, the volcanic units younger than Tvf remain assigned to the Pliocene as per the source map although their radiometric dates would now place them near the base of the Pleistocene.

Unit (map symbol)	Age	Description
Artificial fill (Qaf) *Mapped in Fort Vancouver Unit*	Holocene (recent)	Used for highway and railroad beds, levees, small dams, culverts, and other cultural uses. Mixed clay, silt, sand, gravel, debris, and rubble.
Alluvial deposits (Qal)	Holocene (11,700–present)	Gravel, sand, silt, and clay in active river channels and floodplains.
Alluvium of Columbia River floodplain (Qac) *Mapped in Fort Vancouver Unit*	Holocene (11,700–present)	Unconsolidated sand, silt, and clay underlying the historic Columbia River floodplain. Represents aggradation of the Columbia River associated with rising sea level since the last glacial maximum.
Flow and fan deposits (Qf)	Late Pleistocene–Holocene (126,000–present)	Mixed sand, silt, clay, gravel, and soil deposited by earthflows or debris flows. Form either fan-shaped deposits at the mouths of small gullies or lobes on slopes.
Landslides (Qls)	Pleistocene–Holocene (2.6 MYA–present)	Chaotic mixtures and deformed masses of rock, colluvium, and soil that moved downslope. Almost 400 mapped (9% of map area).
Terrace deposits, younger (Qty)	Late Pleistocene–Holocene (126,000–present	Terraces of silt, sand, and clay deposits. Distinct elevations above the modern floodplain: **Qty** 10 m (33 ft).
Terrace deposits (Qt)	Late Pleistocene–Holocene (126,000–present	Terraces of silt, sand, and clay deposits. Distinct elevations above the modern floodplain: **Qt** 15 m (49 ft)
Terrace deposits, older (Qto)	Late Pleistocene–Holocene (126,000–present	Terraces of silt, sand, and clay deposits. Distinct elevations above the modern floodplain: **Qto** 20 m (66 ft).
Missoula flood deposits (Qff) *Mapped in Fort Vancouver Unit*	Late Pleistocene (19,000–13,000 B.P.)	Unconsolidated, fining-upward sequences of boulders, cobbles, gravel, sand and silt deposits. Underlie Fort Vancouver.
Conglomerate, younger (Qg)	Pleistocene (?) (2.6 million–11,700 years ago)	Conglomerate of well-rounded pebbles and cobbles of basalt, andesite, and dacite. Coarse sand matrix.
Boring Volcanic Field Rocks Outlook basaltic andesite (Qbo)	Pleistocene (1.22–1.28 MYA)	Generally massive flows jointed into crude columns 0.6–1.5 m (2–4.9 ft) in diameter. Inferred to overlie **Qbh**.
Boring Volcanic Field Rocks Outlook tephra (Qvo) (not mapped on GRI poster)	Pleistocene (2.6 million–11,700 years ago)	Ash, scoria, bombs, and breccia of basaltic andesite.
Boring Volcanic Field Rocks Hunsinger basaltic andesite (Qbh) (not mapped on GRI poster)	Pleistocene (1.217–1.190 MYA)	Massive flows with widely spaced planar joints. Distinguished from **Qbo** by rare plagioclase laths up to 0.5 mm (0.02 in) long.
Springwater Formation (QTs) Conglomerate (QTc)	Pliocene–Pleistocene (5.3 million–11,700 years ago)	**QTs**: Pebble, cobble, and boulder conglomerate derived from the Cascade Range and deposited by the ancestral Clackamas River. **QTc**: forms a bench along the Columbia River capped by **Qff**. Overlies **Tt**.

Table 1 (continued). The stratigraphic column for the Fort Vancouver National Historic Site area.

Unit (map symbol)	Age	Description
Boring Volcanic Field Rocks Canemah basalt (Tbc)	Pliocene+ (2.44–2.53 MYA ±180,000–40,000 years).	Massive basalt flows with well-developed to crude columnar jointing. Overlies **Tt** and are overlain only by **Qff**.
Boring Volcanic Field Rocks Canemah tephra (Tvc) (not mapped on GRI poster)	Pliocene	Ash to bomb size tephra with minor basalt flows.
Boring Volcanic Field Rocks Root Creek basaltic andesite (Tbr) (not mapped on GRI poster)	Pliocene (~2.47 MYA ±20,000 years)	Flows overlie **Tvr** and **Tt**. Not overlain by any younger units in map area.
Boring Volcanic Field Rocks Root Creek tephra (Tvr) (not mapped on GRI poster)	Pliocene	Red brown ash, white and yellow scoria, and black volcanic bombs up to 80 cm (31 in) across. Underlies **Tbr**. Overlies **Tt**.
Boring Volcanic Field Rocks Fallsview basaltic andesite (Tbf) (not mapped on GRI poster)	Pliocene (~2.54 MYA ±80,000 years)	Flows interbedded with **Tvf**.
Boring Volcanic Field Rocks Fallsview tephra (Tvf) (not mapped on GRI poster)	Pliocene	Red brown ash, white and yellow scoria, black volcanic bombs up to 40 cm (16 in) across, and breccia interbedded with **Tbf.** Overlies **Tt**.
Boring Volcanic Field Rocks Beaver Creek basaltic andesite (Tbb) (not mapped on GRI posterr)	Pliocene (~2.66 MYA ±50,000 years).	Basalt flows
Troutdale Formation (Tt)	Miocene–Pliocene	Mudstone, siltstone, sandstone, and minor conglomerate and tuff.
CRB: Wanapum Basalt, Frenchman Springs Member, basalt of Sand Hollow (Twfs)	Middle Miocene (15.3 MYA)	Black basalt flows with sparse plagioclase phenocrysts.
CRB: Wanapum Basalt, Frenchman Springs Member, **basalt of Ginkgo (Twfg)** *Mapped in McLoughlin House Unit*	Middle Miocene	Black basalt flows. Abundant plagioclase phenocrysts up to 15 mm (0.59 in) and clusters of phenocrysts (glomerocrysts) up to 20 mm (0.79 in) long. Blocky to columnar jointed, with columns 1–1.75 m (3.3–5.7 ft) in diameter.
CRB: Grande Ronde Basalt, Sentinel Bluffs Member (Tgsb)	Middle Miocene (15.6 MYA)	Black basalt flows exposed along the Willamette River.
CRB: Grande Ronde Basalt, basalt of Winter Water (Tgww)	Middle Miocene	Grey to black basaltic andesite flows. Small plagioclase phenocrysts (<3mm; 0.12 in).

Aggradation of the Columbia River since the last glacial sea-level low stand about 16,000 years ago resulted in non-glacial gravel deposits containing granitic rocks that were used in the construction of the officers' housing (O'Connor et al. 2016). Officers Row, included in the Vancouver National Historic Reserve, became known as Radon Ridge because of the radon gas contained in the granitic rocks (see Graham 2009). Quaternary incision formed the present western Columbia River Gorge, and twentieth century construction of dams and reservoirs further modified the landscape.

Cascade Range volcanism throughout the Quaternary and especially in the late Holocene has left its mark on the present topography. Lahars and large quantities of volcaniclastic sand and gravel have been funneled through the Sandy River at the eastern margin of the Portland Basin. About 1,500 years ago, eruptions of Mount Hood sent at least three lahars down the Sandy River to the Columbia. Snowmelt and rain-on-snow flooding has generated many large flood events. The largest historic flood on the Columbia River occurred in June, 1894, when snowmelt produced a flood discharge of 34,000 m^3/s (1.2 million ft^3/s). The average discharge at the mouth of the river is 7,500 m^3/s (265,000 ft^3/s).

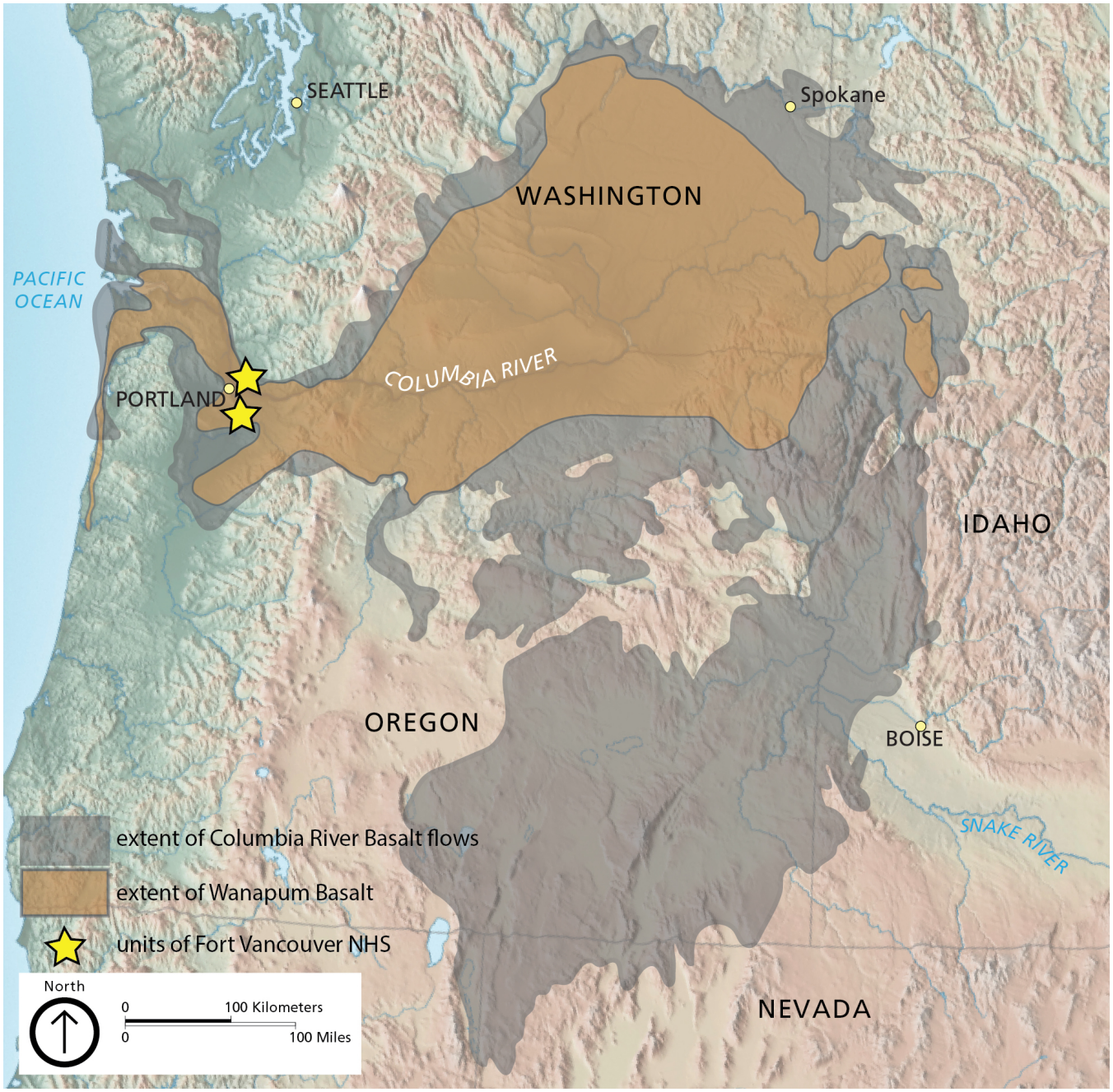


Figure 6. Map showing the distribution of the Columbia River Flood Basalt.
The yellow stars mark the locations of Fort Vancouver National Historic Site units. Map by Trista Thornberry-Ehrlich (Colorado State University) with information from Alt and Hyndman (1995, http://geology.isu.edu/Digital_Geology_Idaho/Module10/mod10.htm; accessed 29 July 2013). Base map by Tom Patterson (NPS), available at http://www.shadedrelief.com/physical/index.htm (accessed 30 July 2013).

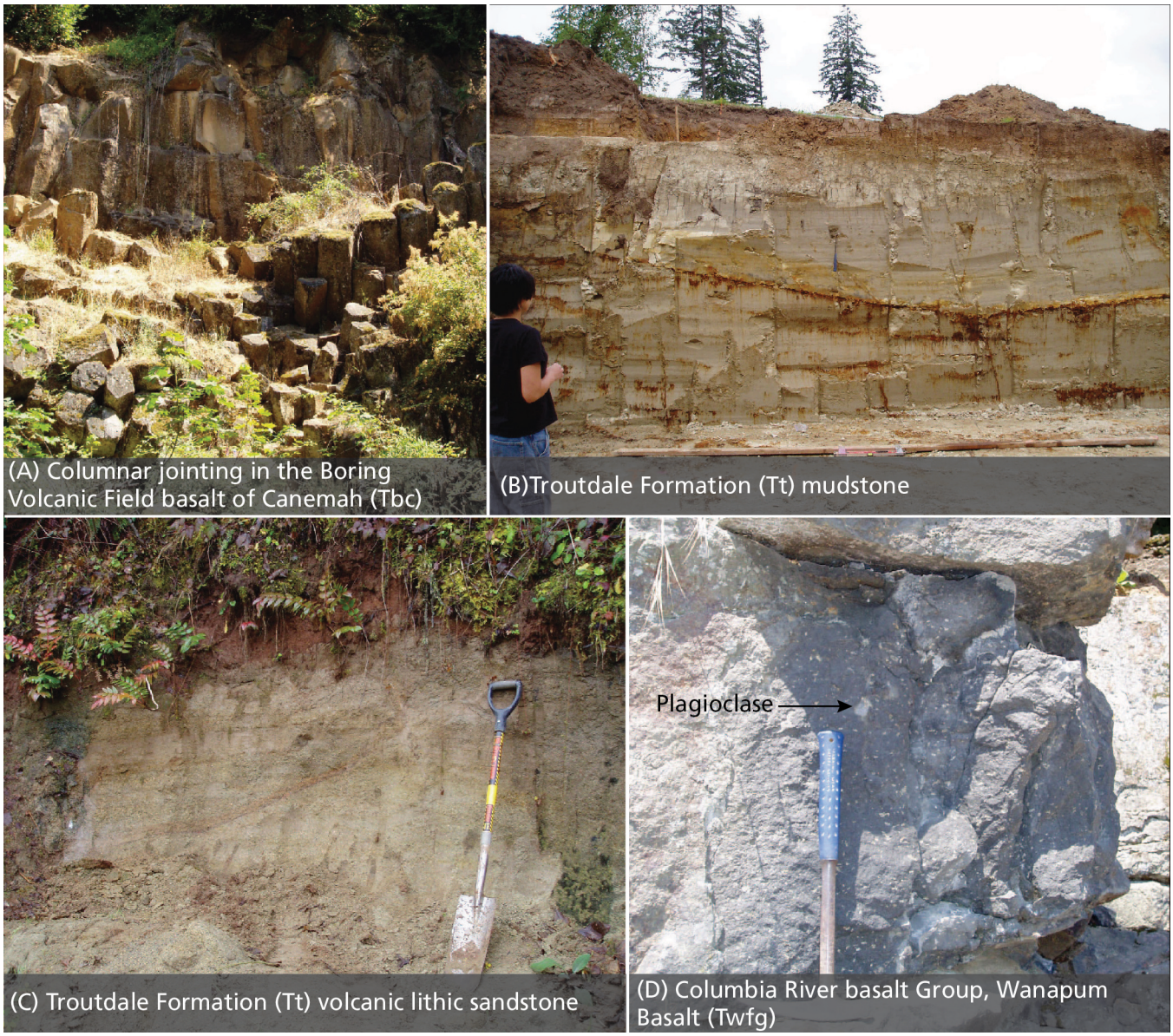


Figure 7. Photographs of exposures of Canemah basalt (Tbc), Troutdale Formation (Tt), and basalt of Ginkgo (Twfg).
(A) Columnar joints in Tbc are 0.6 m (2 ft) to 1.2 m (4 ft) in diameter. (B) This massive mudstone in Tt lacks bedding. (C) Tt consists of volcanic and sedimentary rock fragments. (D) Adjacent to the McLoughlin House, this outcrop of Twfg in the Frenchman Springs Member, Wanapum Basalt Formation contains abundant coarse-grained plagioclase phenocrysts. Photographs from Madin (2009, figures 2, 16, 39, 43, and 52).

When Mount St. Helens erupted in 1980, approximately 34 million m^3 (1,200 million ft^3) of sediment emptied into the Columbia River near Longview, Washington, approximately 64 km (40 mi) downstream from Fort Vancouver.

Most of the upland surfaces in the Fort Vancouver area are blanketed by loess (windblown silt). Paleosols (old soil horizons) in the silt indicate episodic deposition of silt followed by periods of relative stability in which soils developed. Paleosols may provide paleo-ecological data from which to interpret past climatic conditions and events.

LiDAR (Light Detection and Ranging) remote sensing techniques allow mapping volcanic cones, channel deposits, flood gravels, terraces, gravel pits, and other geomorphic features in remarkable detail. In the early 2000s, the United States Geological Survey (USGS) acquired LiDAR for the Columbia River floodplain to

30 m (100 ft) above sea level (see Graham 2009). The Oregon Department of Geology and Mineral Industries (DOGAMI) acquired LiDAR for the southern part of the Portland Basin (see Graham 2009). In 2010, the Army Corps of Engineers acquired LiDAR for approximately 7,345 km^2 (2,836 mi^2) of portions of Oregon, Washington, Idaho, and Montana within the Columbia River drainage (https://data.noaa.gov/dataset/2010-us-army-corps-of-engineers-usace-portland-district-columbia-river-LiDAR, accessed 28 August 2017).

McLoughlin House Unit

Across the Columbia River from Fort Vancouver, the McLoughlin and Barclay houses rest on Singer Hill, which is part of the larger Oregon City Plateau (fig. 1). The plateau forms the southeastern border of the Portland Basin (fig. 3). The Willamette River curls around the northern edge of the Oregon City Plateau, and the impressive, horseshoe-shaped Willamette Falls may be seen from the McLoughlin House unit (fig. 8). The Columbia River Basalt Group underlies the plateau and forms Willamette Falls, whereas the younger basalt of Canemah (**Tbc**), part of the Boring Volcanic Field, forms the surface of the plateau (fig. 7; Madin 2009). The bluff behind the McLoughlin and Barclay houses consists of 4.5–6 m (15–20 ft) of exposed Ginkgo basalt that is part of the Frenchman Springs Member of the Wanapum Basalt Formation, Columbia River Basalt Group (**Twfg**) (fig. 9). Willamette Falls marks the contact between the Wanapum Basalt and underlying Grande Ronde Basalt (**Tgsb**) of the Columbia River Basalt Group (Madin 2009).

Three northwest-trending normal faults fracture the Portland Hills (fig. 3, fig. 10). From north to south, these faults include the Portland Hills Fault, the Oatfield Fault, and the Bolton Fault (fig. 11; Madin 2009). The Oatfield Fault is not exposed in the region between the Fort Vancouver unit and the McLoughlin House unit. The Bolton Fault borders the northeastern edge of the Oregon City Plateau. Rock units on the northern side of the fault have moved down relative to rocks on the southern side of the fault (fig.13).

Geologic Significance and Connections

Fort Vancouver Unit

Glacial Lake Missoula flood deposits (**Qff**) represent a unique connection between geology and the development of Fort Vancouver. In the Pleistocene, Lake Missoula formed behind ice dams that blocked the Clark Fork tributary to the Columbia River in Idaho. When filled to its maximum, Lake Missoula covered approximately 7,500 km^2 (2,900 mi^2) and was almost 610 m (2,000 ft) deep at the ice dam and 300 m (950 ft) deep in the Missoula Valley (Alt 2001; Allen et al. 2009). The lake contained as much water as today's lakes Erie and Ontario combined (Booth et al. 2004).

When the ice dams failed, and they failed every few decades, Lake Missoula emptied at a rate of about 64 million liters (17 million gallons) per second. A towering mass of ice, water, mud, and debris would sweep down the Clark Fork, across Spokane Valley, and through the Columbia Gorge to the sea (Bretz 1969; Waitt 1985; Baker 1987; Allen et al. 2009). Missoula floods scoured as much as 34,252 km^2 (13,225 mi^2) of the Columbia Plateau (an area slightly larger than the state of Maryland). The turbulent floodwaters attacked planes of weakness in the bedrock, ripped up chunks of basalt, and gouged the bedrock to form the magnificent Channeled Scablands of eastern Washington (fig. 13; see also the GRI report for Whitman Mission National Historic Site by Graham 2014a). Flood currents transformed the bedload (material transported along the river bed) into gigantic, three-story high ripple marks, and scattered 200-ton boulders from Idaho to the Willamette Valley. The hydraulic force and concussion of floodwaters cascading over immense cataracts formed enormous plunge pools (Bretz 1969). For example, Dry Falls, one of many exceptional cataracts that formed in the floods, measures 120 m (360 ft) high and 5.5 km (3.3 mi) wide, which is about five times the width of Niagara Falls (Baker 1987). Palouse Falls in southeastern Washington displays hanging flood-created coulees, cataracts, plunge pools, kolk created potholes (potholes created by an underwater vortex), rock benches, buttes and pinnacles typical of the Channeled Scablands (fig. 14).

As much as 10 million m^3 (350 million ft^3) of flood waters careened through the Columbia River Gorge and into the Portland Basin, carving channels and depositing extensive gravel sheets (Evarts et al. 2009a). Flood velocities reached 35 m^3/s (1,200 ft^3/s) and depths approached 300 m (1,000 ft) in the Portland Basin (Benito and O'Connor 2003; Evarts et al. 2009a). Boulders exceeding 5 m (16 ft) in diameter were transported by the floodwaters into the eastern Portland Basin where boulder, sand, and gravel bars (**Qff**) are as much as 70 m (230 ft) thick. In other areas, floodwaters formed gravel bars hundreds of meters high (Bretz 1928b). As floodwaters receded, layers of silt, sand, and gravel were deposited above the older Columbia River terrace deposits (**QTc**). Fort Vancouver is located on a terrace formed in Missoula flood gravel deposits (Evarts et al. 2009a).

At least 40 cataclysmic floods of tremendous force and dimensions surged across the Columbia River drainage basin (Bretz 1928a, 1930; Pardee 1942; Allen



Figure 8. Photograph of Willamette Falls on the Willamette River.
The river plunges 14 m (46 ft) over the top of the Sentinel Bluffs Member of the Grande Rhonde Basalt (Tgsb). The tree-covered cliffs in the background consist of basalt of Ginkgo basalt flow of the Frenchman Springs Member of the Wanapum Basalt (Twfg). A sacred site for American Indians, Willamette Falls also provided hydraulic power for the mill constructed by the Hudson's Bay Company. Photograph by John Graham (Colorado State University).



Figure 9. Photograph of basalt of Ginkgo (Twfg) forms the bluff behind the McLoughlin House unit. These dense, Miocene basalt flows are part of the Columbia River Basalt Group. Vertical fractures that might contribute to potential rockfall are rare in this outcrop. Photograph by John Graham (Colorado State University).

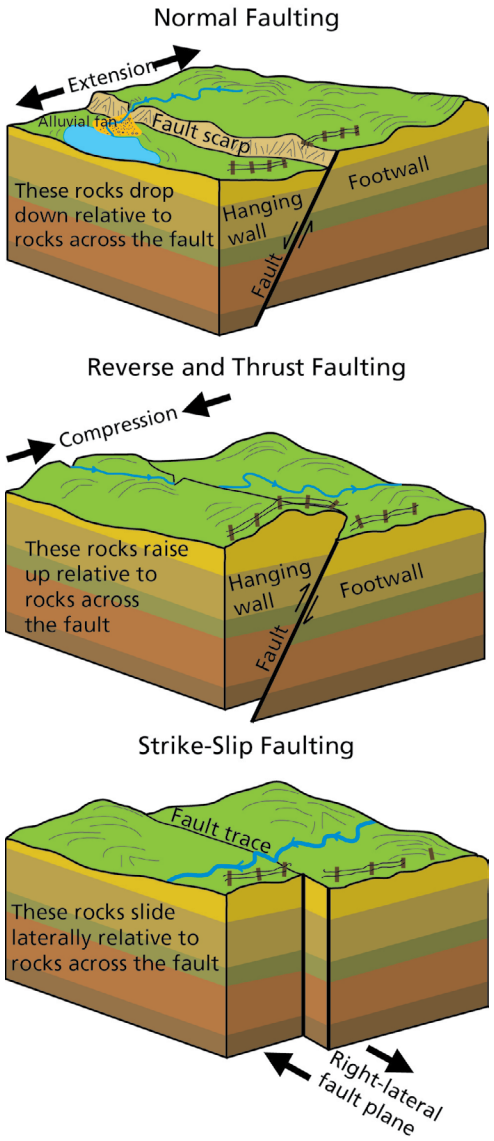


Figure 10. Illustrations of the three basic fault types. Movement occurs along a fault plane. Footwalls are below the fault plane and hanging walls are above. In a normal fault, such as the Bolton Fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging wall up relative to the footwall. A thrust fault is similar to a reverse fault, but has a dip angle of less than 45°. In a strike-slip fault, the relative direction of movement of the opposing plate is lateral. When movement across the fault is to the right, it is a right-lateral (dextral) fault, as illustrated above. When movement is to the left, it is a left-lateral (sinistral) fault. A strike-slip fault between two plate boundaries is called a transform fault. Reverse, thrust, and strike-slip faults were not recognized on the source maps used for the GRI GIS map. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

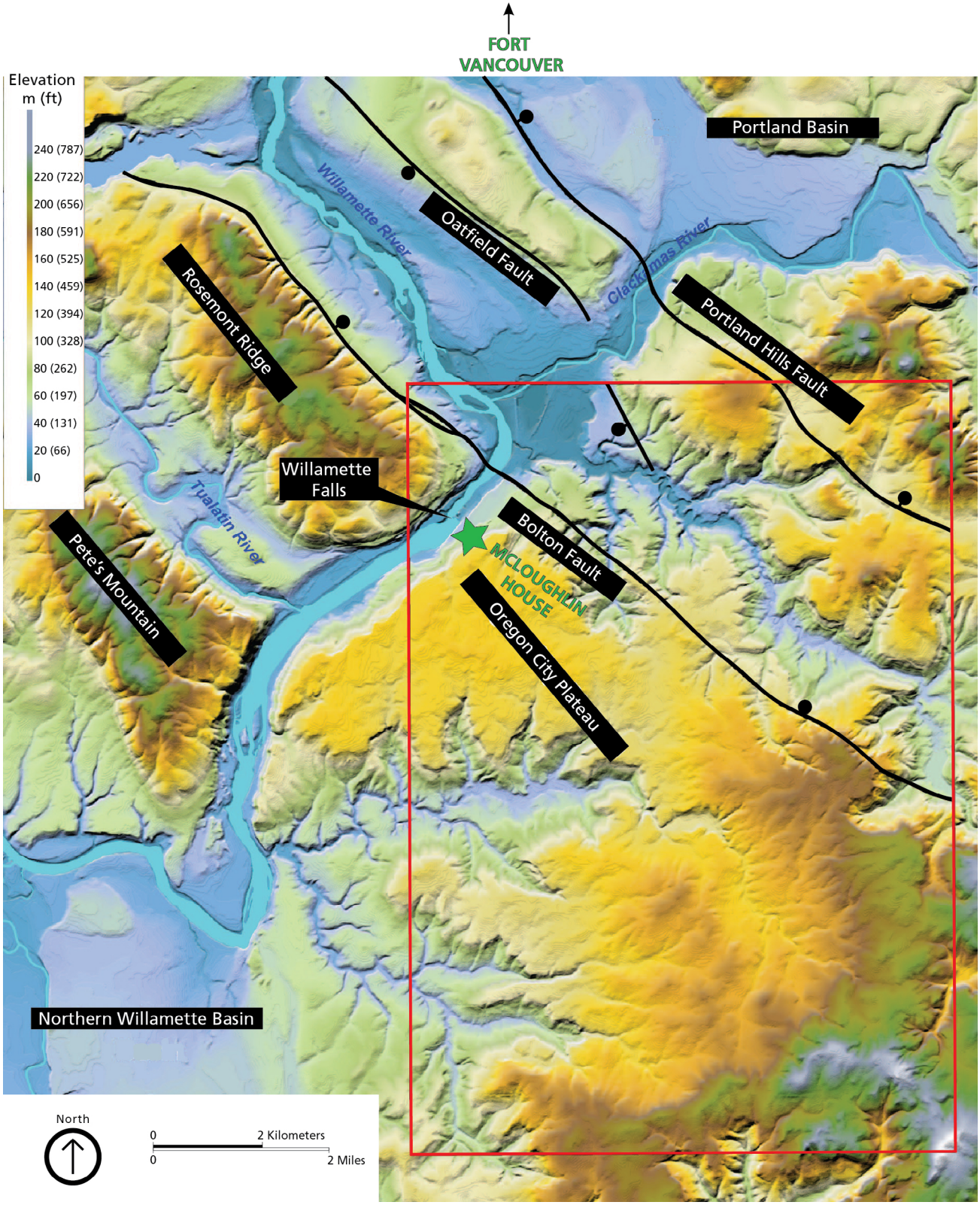


Figure 11. The Portland Hills Fault, Oatfield Fault, and Bolton Fault displace the Portland anticline. The anticline is between the McLoughlin House and Fort Vancouver units, Fort Vancouver National Historic Site. The red box is the Oregon City quadrangle. The heavy black lines are major faults. The black circles mark the downthrown side of normal faults. Movement along the Bolton Fault may have been responsible for Willamette Falls, which has since receded southward. The green star is the approximate location of the McLoughlin House unit. Map by Trista Thornberry-Ehrlich (Colorado State University) after Madin (2009, figure 58).

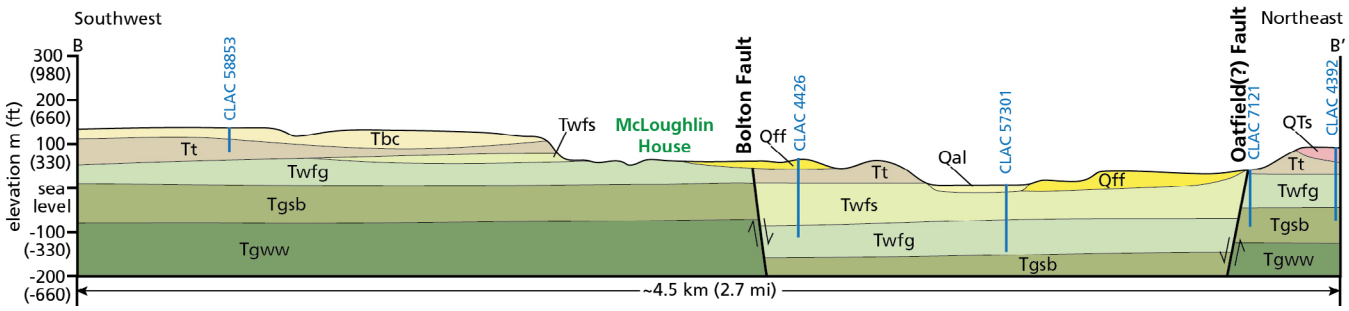


Figure 12. Geologic cross section B-B′.
The section identifies the stratigraphic units below the McLoughlin House and the offset of stratigraphic units adjacent to the Bolton Fault. The Bolton Fault is a normal fault (fig. 10) with units on the northeast side of the fault moving down relative to units on the southwest side of the fault. "CLAC" lines represent data points from water wells. The cross section is labeled on the geologic map of the Oregon City quadrangle (Madin 2009) and is located approximately 600 m (2,000 ft) east of the McLoughlin House. The cross section is not on the GRI GIS map. Modified from Madin (2009).

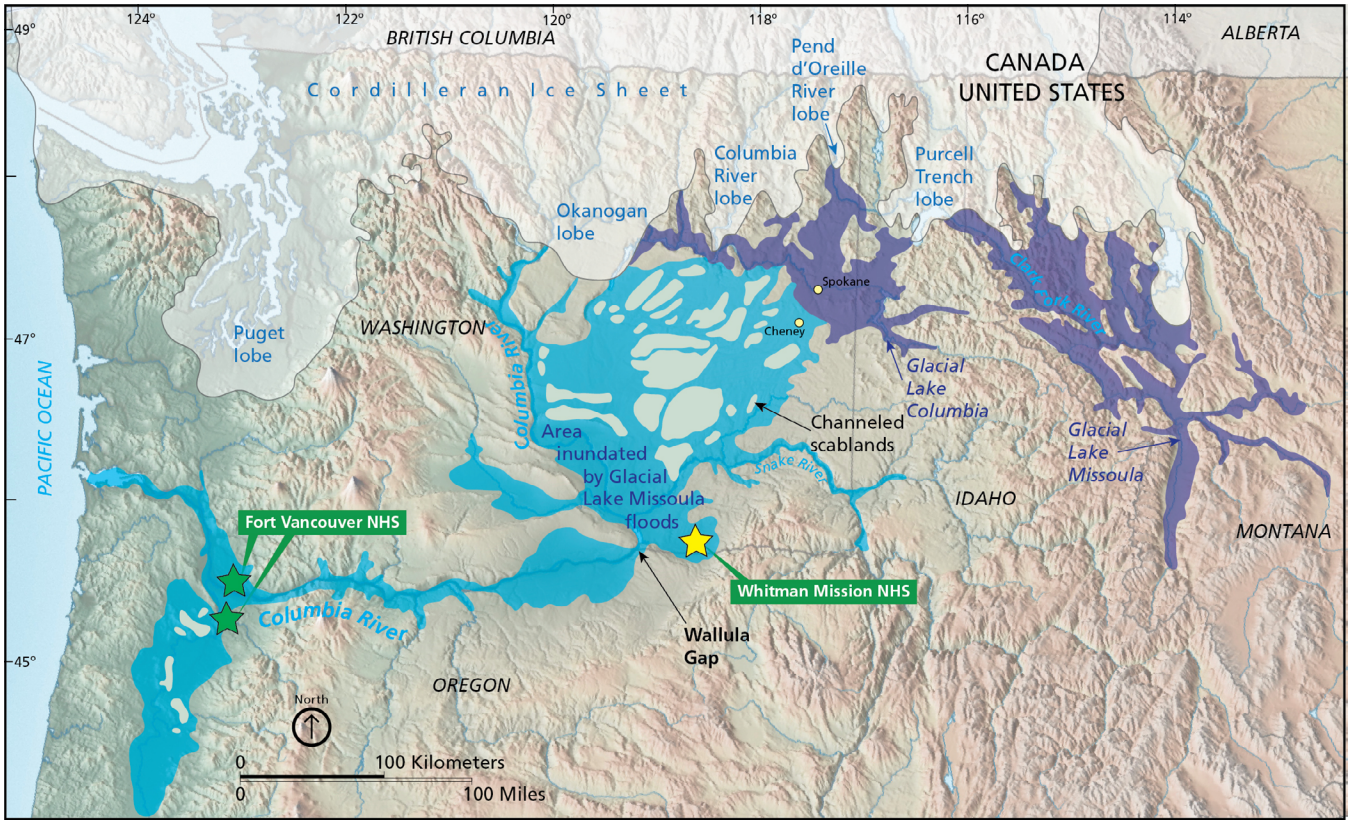


Figure 13. Map of the extent of glacial Lake Missoula and its floodwaters.
During the Pleistocene ice ages, the Purcell Trench lobe of the Cordilleran Ice Sheet periodically flowed south, forming ice dams that blocked the Clark Fork River and allowing glacial Lake Missoula to fill. Similarly, glacial Lake Columbia formed behind ice dams from the Okanogan and Columbia River lobes that blocked what is now the Columbia River. When the ice dams failed, catastrophic floods swept across eastern Washington, through the Columbia River Gorge, and into the Portland Basin. 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. Graphic by Trista Thornberry-Ehrlich (Colorado State University), created using information 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).

et al. 2009). Today, the glacial Lake Missoula floods and the enormous features they produced are accepted as excellent examples of catastrophic events punctuating the geologic record. In the 1920s, however, J. Harlen Bretz ignited a firestorm of controversy in the geologic community when he first proposed the idea of a catastrophic flood. For decades, early-20th-century geologists had moved away from "catastrophism" (such as the Biblical flood) and shifted their thinking toward "uniformitarianism," a geologic theory wherein landscapes are formed by "slow" geologic processes (Alden et al. 1927; Bretz 1928a, 1930; Allen et al. 2009). Although Bretz documented his colossal "Spokane Flood" with detailed field evidence, his hypothesis was not accepted until 1942 (Pardee 1942).

The story of J. Harlen Bretz and the extraordinary Pleistocene floods from glacial Lake Missoula provide excellent interpretive opportunities at Fort Vancouver National Historic Site. For example, the Missoula flood gravels influenced the location of the Hudson's Bay Company. McLoughlin built Fort Vancouver on terrace gravels to be out of the range of seasonal flooding (Evarts et al. 2009a). The silt distributed by these catastrophic floods contributed to the remarkable agricultural conditions in today's Willamette Valley. At Fort Vancouver, farming operations took advantage of the floodplain (fig. 15). The fertile land adjacent to the Columbia River is considered to be a primary interpretive theme for the park (NPS 2017). Until twentieth-century construction of dams and floodplain levees, overbank deposits and bar accretion continued to supply the floodplain with sediment and nutrients. The relatively flat floodplain also provided an excellent location for Pearson Air Field (fig. 1).

Holocene deposits at Fort Vancouver may be among the first features studied by geologists in the Pacific Northwest. In 1841, the Wilkes expedition entered the Columbia River and their ship, the Peacock, floundered on a sand bar in the mouth of the river. James Dwight Dana swam ashore and became the first geologist to set foot in the Pacific Northwest (Jim O'Connor, USGS, hydrologist, personal communication, 24 November 2009). Dana, a famous mineralogist and volcanologist, eventually reached Fort Vancouver and documented the late Holocene processes of natural levee formation and the process of groundwater flooding in the floodplain behind the levees (see Graham 2009).

The NPS manages Ice Age Floods National Geologic Trail (established in 2009) to help tell the geologic story of the glacial Lake Missoula floods. This trail is the nation's first National Geologic Trail and consists of a network of routes that trace the outstanding geological consequences of the glacial Lake Missoula floods of the most recent glacial period. The central route of the trail bisects the Columbia Gorge and lies adjacent to Fort Vancouver National Historic Site (NPS 2014).

McLoughlin House Unit

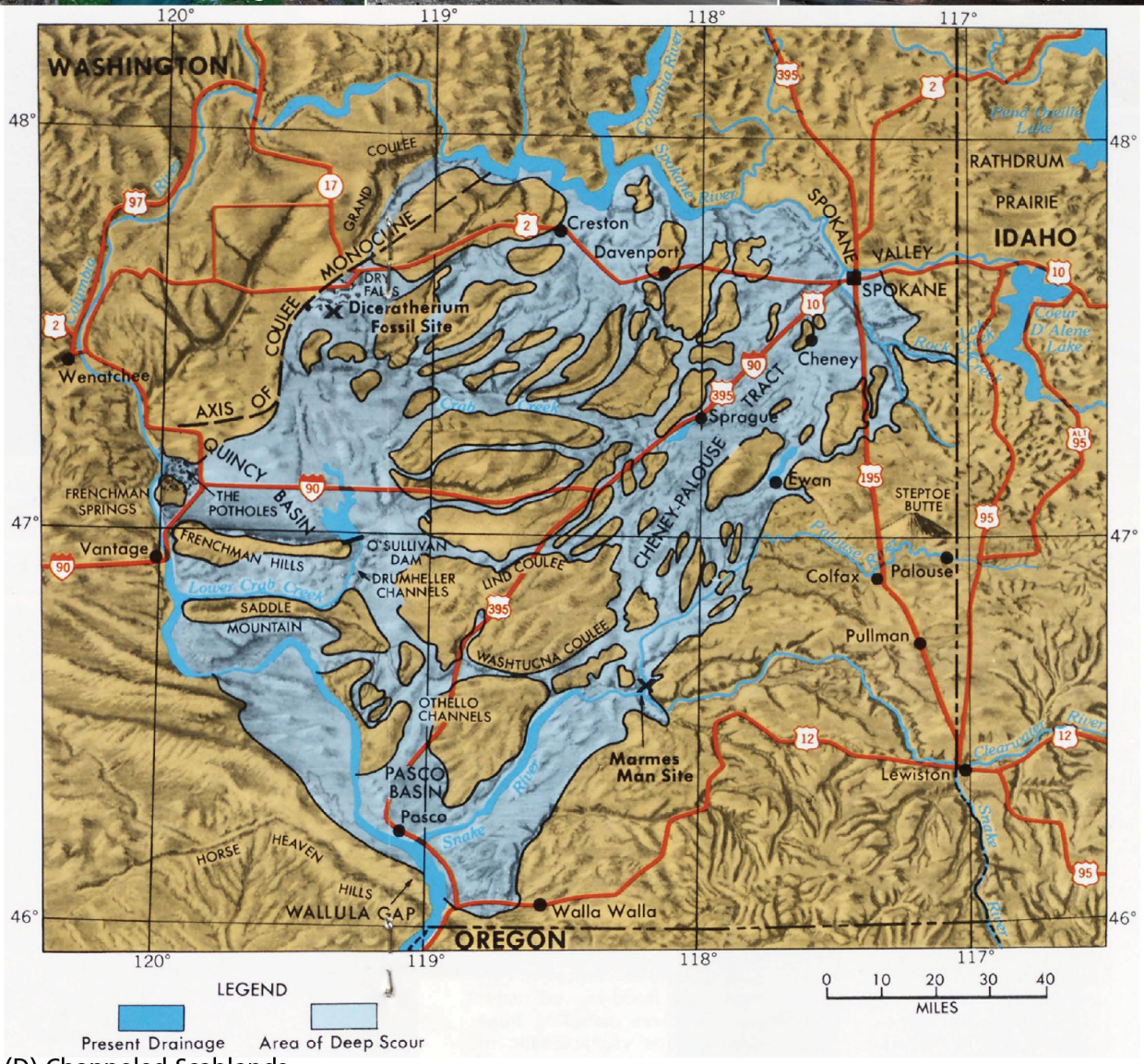
The voluminous outpourings of Columbia River Basalt, as well as the catastrophic glacial Lake Missoula floods, connect the McLoughlin House unit of Fort Vancouver National Historic Site to the current landscape. As much as 75 m (250 ft) of the Ginkgo basalt within the Frenchman Springs Member of Wanapum Basalt (**Twfg**) underlies the Oregon City area, including the McLoughlin House unit (fig. 9). The black basalt flows separate the underlying 15.6 million year old basalt of the Sentinel Bluffs Member of the Grande Rhonde Basalt (**Tgsb**) from the overlying 15.3 million year old Sand Hollow basalt of the Frenchman Springs Member (**Twfs**) (fig. 12).

Eruptions of Grande Ronde Basalt (**Tgsb**, **Tgww**, **Tcu**) lasted less than 1 million years yet spread over approximately 155,000 km^2 (60,000 mi^2) (fig. 6). The volume of the 120 Grande Ronde Basalt flows has been estimated at 146,000 km^3 (35,000 mi^3), which is enough lava to circle the globe at the Equator twice with a tube of lava 0.6 km (1 mi) in diameter (Bishop 2003). Some flows rank among the longest on Earth, traversing 180 km (300 mi) from eastern Oregon and Washington to the Pacific coast. Along the way, they torched forests and filled portions of the Willamette Valley that would become Portland. Individual flows now form the cliffs of the Columbia River Gorge.

Wanapum basalt flows followed the path of the earlier Grande Ronde Basalt (fig. 6). Eroded from hilltops or buried by younger sediments in valleys, the Wanapum Basalt lacks the exposure of the Grande Ronde Basalt. Exposures of Wanapum Basalt occur primarily near Portland, in the Columbia River Gorge, at Silver Falls State Park, and near Salem (Bishop 2003). Crown Point, a promontory east of Portland in the Columbia River Gorge, may be the most impressive exposure of the Wanapum Basalt. All of the 340 vertical meters (1,100 ft) at Crown Point consist of one basalt flow within the Priest Rapids Member. The primary Wanapum Basalt flows that inundated the Portland area and now underlie the Oregon City Plateau and the McLoughlin House consist of the basalt of Ginkgo in the Frenchman Springs Member (GIS layer **Twfg**).

Over the millions of years between the Miocene and the Pleistocene, the Portland Basin landscape changed significantly (Evarts et al. 2009a). By 2 million years ago, the Willamette River had eroded a narrow gap through the Oregon City Plateau before being joined by the Clackamas River north of the Bolton Fault. The





(D) Channeled Scablands

Figure 14. Photographs (A-C) and a map (D) of features resulting from Pleistocene ice age floods. (A) Palouse Falls in southeastern Washington. (B) Strandlines, or shoreline benches, cut by waves on glacial Lake Missoula record various lake levels. (C) Long gravel ridges near Camas Hot Springs, Montana, record giant ripple marks formed by the flood waters. (D) Map of the Channeled Scablands. Figures A and B are from the Ice Age Floods Institute, available at http://iafi.org/floods-features-map/ (accessed 24 March 2017). Figures C and D are from the USGS publication, The Channeled Scablands of Eastern Washington (USGS 1976), available at https://pubs.usgs.gov/gip/70007447/report.pdf (accessed 24 March 2017).



Figure 15. Photograph of prairie topography and Fort Vancouver in the Fort Vancouver unit. The prairie vegetation grows on alluvium of the Columbia River floodplain (Qac). According to Theresa Langford, curator, Fort Vancouver National Historic Site, the prairies were maintained through fire by indigenous peoples. The relatively flat topography provided an ideal location for the adjacent Pearson air field. Photograph by John Graham (Colorado State University).

Willamette/Clackamas River flowed north past present-day Portland and entered the Columbia River opposite the future site of Fort Vancouver. When the glacial Lake Missoula floods surged through the Columbia River Gorge and spilled into the Portland Basin, floodwaters backed-up the Willamette River and gushed through the Oregon City Water Gap, flooding the Willamette Valley from Portland to Eugene, Oregon. Willamette Valley was transformed into a lake 160 km (100 mi) long, 100 km (60 mi) wide, and 90 m (300 ft) deep (Bishop 2003). In 2012, the Oregon DOGAMI produced the first LiDAR map that showed the extent of the Missoula floods in the Portland area (Burns and Coe 2012). The DOGAMI map, coupled with the 49 m (160 ft) elevation of the McLoughlin House from the GIS map, shows that the Missoula floods submerged the acreage of the McLoughlin House unit but did not inundate the top of the Oregon City Plateau (fig. 16).

By the time the McLoughlin and Barclay built houses next to the Willamette River, the river channel had scoured to bedrock, and Willamette Falls, known as "Niagara West," cascaded 12–15 m (40–50 ft) over Columbia River Basalt. The present cataract plunges 14 m (46 ft) over the top of the Sentinel Bluffs Member of the Grande Ronde Basalt (**Tgsb**) and marks the contact between the Grande Ronde Basalt and the basalt of Ginkgo in the Frenchman Springs Member of the Wanapum Basalt (**Twfg**). Movement on the northwest–southeast oriented Bolton Fault, combined with the Missoula floods, may have contributed to the origin of Willamette Falls (Madin 2009). Waterfalls tend to migrate upstream over time because of erosion, which

may explain why the present falls are located 1,500 m (4,900 ft) upstream from the Bolton Fault (see GRI poster). The majority of migration at Willamette Falls probably occurred during the Missoula floods when as much as 250 km^3 (60 mi^3) of water flowed past this site (Madin 2009).

American Indians consider Willamette Falls to be a sacred place. Legends teach that the falls were placed there by a great god so their people would have fish to eat all winter. Local tribes built villages in the area because salmon were plentiful. In the early summer, American Indians still harvest Pacific Lamprey at Willamette Falls.

The hydraulic power of the falls was not lost on the Hudson's Bay Company. Fur traders noted the falls in 1810, and McLoughlin established a land claim at the falls in 1829. In 1841, Joe Meek carved his name into the basalt, becoming the first to leave graffiti at the falls. In 1842, Oregon City was founded, and the Hudson's Bay Company built a mill at the falls.

Although the Hudson's Bay Company left Oregon in 1846, commerce on the Willamette River continued. Willamette Falls marked the end of the line for boat traffic, and river boat captains had to choose to dock at either Oregon City or Linn City, founded in 1843 on the west shore of the river. The two cities vied for the lucrative steamboat traffic and trade until the winter of 1861 when catastrophic flooding destroyed Linn City. In 1873, completion of the Willamette Falls Locks allowed river traffic upstream from the falls. Industrialization of the area took its toll on the salmon and steelhead populations, prompting the construction of a fish ladder in 1882. A new fish ladder was built in 1971.

Willamette Falls became responsible for the first long distance transmission of electrical energy in 1888 when Willamette Falls Electric Company (renamed Portland General Electric) built a hydroelectric facility at the falls and a 23-km (14-mi) long transmission line to Portland. Paper mills began operating at the falls in 1886. As of July 2017, one paper mill was still in operation on the West Linn side of the river. The falls continue their upstream migration.

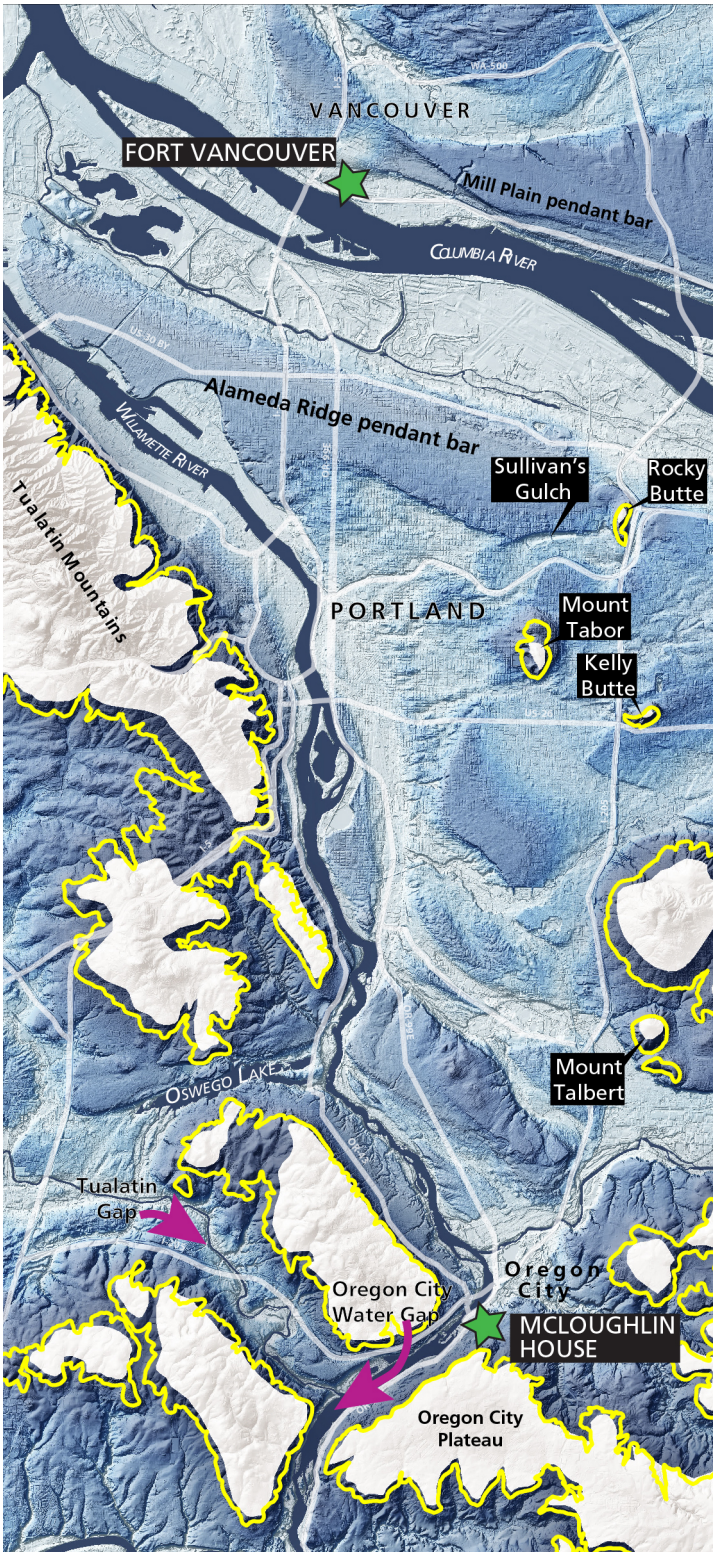


Figure 16. Map showing the maximum extent of glacial Lake Missoula floodwaters in the area of the park. The yellow line represents the 400-ft elevation contour; areas in blue mark the maximum inundation of the Missoula floodwaters in this area; and areas outside the blue, such as portions of the Oregon City Plateau, were not flooded by Missoula floodwaters. Redrafted by Trista Thornberry-Ehrlich (Colorado State University) using LiDAR-derived map by Burns and Coe (2012), available at http://www.oregongeology.org/pubs/ims/p-ims-036.htm (accessed 2 March 2017).

Geologic Features, Processes, and Resource Management Issues

These geologic features and processes are significant to the landscape and history of Fort Vancouver National Historic Site. 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 2009), participants (see Appendix A) identified the following features, processes, and resource management issues. Tables 2, 3, 4, and 5 discuss the features, processes, and issues associated with specific geologic units mapped within the historic site and throughout the region.

Geologic Features and Processes

Features specific to the units mapped within Fort Vancouver National Historic Site include:

- Lacustrine (lake) features.
- Fluvial (river) features.
- Paleontological resources.
- Glacial features.
- Basalt flow features.

Regional geologic features and processes include:

- Alpine glacial features.
- Dunes.
- Coastal features.
- Willamette Falls.
- Faults.
- Earthquakes.
- Slope movements (landslides).
- Volcanic features.
- Features associated with global climate change.

Geologic Resource Management Issues

Scoping meeting participants discussed the following issues specific to the units mapped within Fort Vancouver National Historic Site and regional geologic issues that might influence management decisions.

- Flooding.
- Inventory, monitoring, and protection of paleontological resources.
- Slope movement and infrastructure.
- Radon exposure.
- Earthquakes.
- Volcanic activity.
- Global climate change.
- Coastal features.
- Faults.
- Earthquakes.
- Slope movement (landslides).
- Volcanic activity.
- Issues associated with global climate change.

Geologic Resource Management

The park's Foundation Document was completed in 2017 (NPS 2017), and a Natural Resource Condition Assessment and Resource Stewardship Strategy is in the process of being completed (Marcia Davis, NPS Pacific West Regional Office, geologist, written communication, 22 June 2017). Cultural landscape restoration and management are also addressed in several publications and are considered key resources and key issues for the park (NPS 2017). Cultural landscape inventories by Owens (2007) and Owens and Cain (2009) are available on the following IRMA websites: https://irma.nps.gov/DataStore/Reference/Profile/2184945 and https://irma.nps.gov/DataStore/Reference/Profile/2184921, respectively.

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

Resource managers may find *Geological Monitoring* (Young and Norby 2009; http://go.nps.gov/geomonitoring) useful for addressing geologic resource management issues. The manual provides guidance for monitoring vital signs—measurable parameters of the

overall condition of natural resources. Each chapter covers a different geologic resource and includes detailed recommendations for resource managers, suggested methods of monitoring, and case studies.

The Geoscientists-in-the-Park and Mosaics in Science programs are internship programs to place scientists (typically undergraduate students) in parks to complete geoscience-related projects that may address resource management issues. Refer to the programs' websites at http://go.nps.gov/gip and https://www.nps.gov/subjects/youthprograms/mosaics.htm for more information. As of December 2016, no Geoscientists-in-the-Park or Mosaics in Science projects had been completed for Fort Vancouver National Historic Site.

Resource Management Guidance for Potential Geological Hazards

Coastal Resource Management and Planning

The Coastal Adaptation Strategies Handbook (Beavers et al. 2016; https://www.nps.gov/subjects/climatechange/coastalhandbook.htm) summarizes the current state of NPS climate adaptation and key approaches currently in practice or considered for climate change adaptation in coastal areas in order to guide adaptation planning in coastal parks. The chapters focus on policy, planning, cultural resources, natural resources, facility management, and communication/education. The handbook highlights processes, tools and examples that are applicable to many types of NPS plans and decisions. 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, which can provide insight for parks with boundaries that may shift with changing shorelines (http://www.nps.gov/applications/npspolicy/DOrders.cfm); and NPS Reference Manual #39-2: Beach Nourishment Guidance (Dallas et al. 2012) for planning and managing nourishment projects.

The Cultural Resources Climate Change Strategy (Rockman et al. 2016; https://www.nps.gov/subjects/climatechange/culturalresourcesstrategy.htm) sets out 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.

Fluvial Geomorphology

The Fort Vancouver unit in Fort Vancouver National Historic Site borders the Columbia River, and visitors have the opportunity to view this dynamic river and features including in-channel sand bars and islands and anthropogenic activities associated with channel maintenance, such as dredging (Peterson et al. 2014). 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 Resource Inventory, Monitoring, and Protection

All paleontological resources are non-renewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act (see Appendix B). As of May 2017, Department of the Interior regulations associated with the Act were awaiting finalization and surnaming.

Although the paleontological resources at Fort Vancouver National Historic Site are maintained in the archeology collections, future archeology excavations should also include a paleontological survey. 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 Fort Vancouver National Historic Site, a variety of publications and resources provide park-specific or servicewide 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, including Fort Vancouver National Historic Site.

Table 2. Geologic features and processes associated with geologic units mapped within the Fort Vancouver and McLoughlin House units, Fort Vancouver National Historic Site.

Map Unit (symbol)	Features and Processes
Artificial Fill (Qaf) *Mapped in Fort Vancouver Unit*	**Lacustrine (Lake) Features** The pond that existed when the fort was built became a landfill that now contains abundant archeological artifacts.
Alluvium of Columbia River floodplain (Qac) *Mapped in Fort Vancouver Unit*	**Fluvial (River) Features** Coarsening upward sequences represent aggradation of the Columbia River associated with rising sea level and abundant sediment supply since the end of the last glacial maximum. Flood deposits formed the relatively flat floodplain.
Alluvium and Artificial Fill (Qaf, Qac) *Mapped in Fort Vancouver Unit*	**Paleontological Resources** Paleontological specimens in the park's museum collection include pollen, invertebrate fossils, and vertebrate fragments transported into the area either by natural processes or by humans and deposited in artificial fill (**Qaf**), alluvium (**Qac**), or personal collections (fig. 17). These specimens are maintained in the park's archeology collection, which consists of roughly 2 million specimens. At least eight of the specimens in the park collection that contain the word "fossil" may have come from personal collections and consist of concretions containing impressions of bivalves of the family Pectinidae, genus ***Patinopectin*** (fig. 17; Fay et al. 2009). Pectinidae genera are well-known from Eocene–Miocene strata of the Pacific Northwest coast, such as the Astoria Formation. The collection includes three specimens of partially fossilized faunal tibia whose marrow has been replaced with calcium carbonate (fig. 17). Fort Vancouver served as a cultural crossroads, and many of the fossils occurred within cultural contexts as artifacts (notched, drilled, or incised items) or ornaments crafted from bone, shells, or teeth. About 700 archeological specimens incorporate invertebrate shells including mother of pearl, tortoise shell, ***Haliotis*** (abalone), "dentalium" (family Dentallidae), whelk, and cockle shells (Fay et al. 2009). Bones or animal teeth associated with over 5,000 specimens include knife handles, spoons, gaming pieces, buttons, beads, spear points, fishing points, and a whistle. Mortar used in the 1832 construction of the Powder Magazine's foundation incorporated coral from Hawaiian reefs (Lummio and Tissot 2006; Fay et al. 2009). Analysis of approximately 4,000 samples identifiable on the genus-level revealed that the majority of the samples consisted of Porites (99.4%), followed by ***Leptastrea*** (0.33%) and ***Pocillopora*** (0.23%), typical of a live Hawaiian reef (Lummio and Tissot 2006). The coral may have been transported to Fort Vancouver as ballast.
Missoula flood deposits (Qff) *Mapped in Fort Vancouver Unit*	**Glacial Features** Glacial Lake Missoula outburst flood deposits (**Qff**) form the terrace upon which Fort Vancouver was built and gravel bars consisting of boulders and cobbles. Most of the clasts derived from the Columbia River Basalt Group, but also include re-worked Troutdale Formation (**Tt**) clasts and Cascade Range volcanic rocks (Evarts and O'Conner 2008). Rare exposures illustrate flood deposit features including fining-upward sequences up to 1.0 m (3.3 ft) thick of pebbles, sand, and silt, topped by well-developed paleosols from 5.0 cm (2.0 in) to 30 cm (12 in) thick. Rare glacial erratics consisting of granitic rocks have been found in the fine-grained deposits at elevations as much as 115 m (377 ft).
Columbia River Basalt Group, Wanapum Basalt, Frenchman Springs Member, basalt of Ginkgo (Twfg) *Mapped in McLoughlin House Unit*	**Basalt Flow Features** Black basalt with abundant plagioclase phenocrysts as much as 15 mm (0.59 in) wide and aggregates of plagioclase phenocrysts (glomerocrysts) as much as 20 mm (0.79 in) long (figs. 7, 9). Typically, the flows are blocky to columnar jointed, with columns 1.0–1.8 m (3.3–5.9 ft) in diameter.

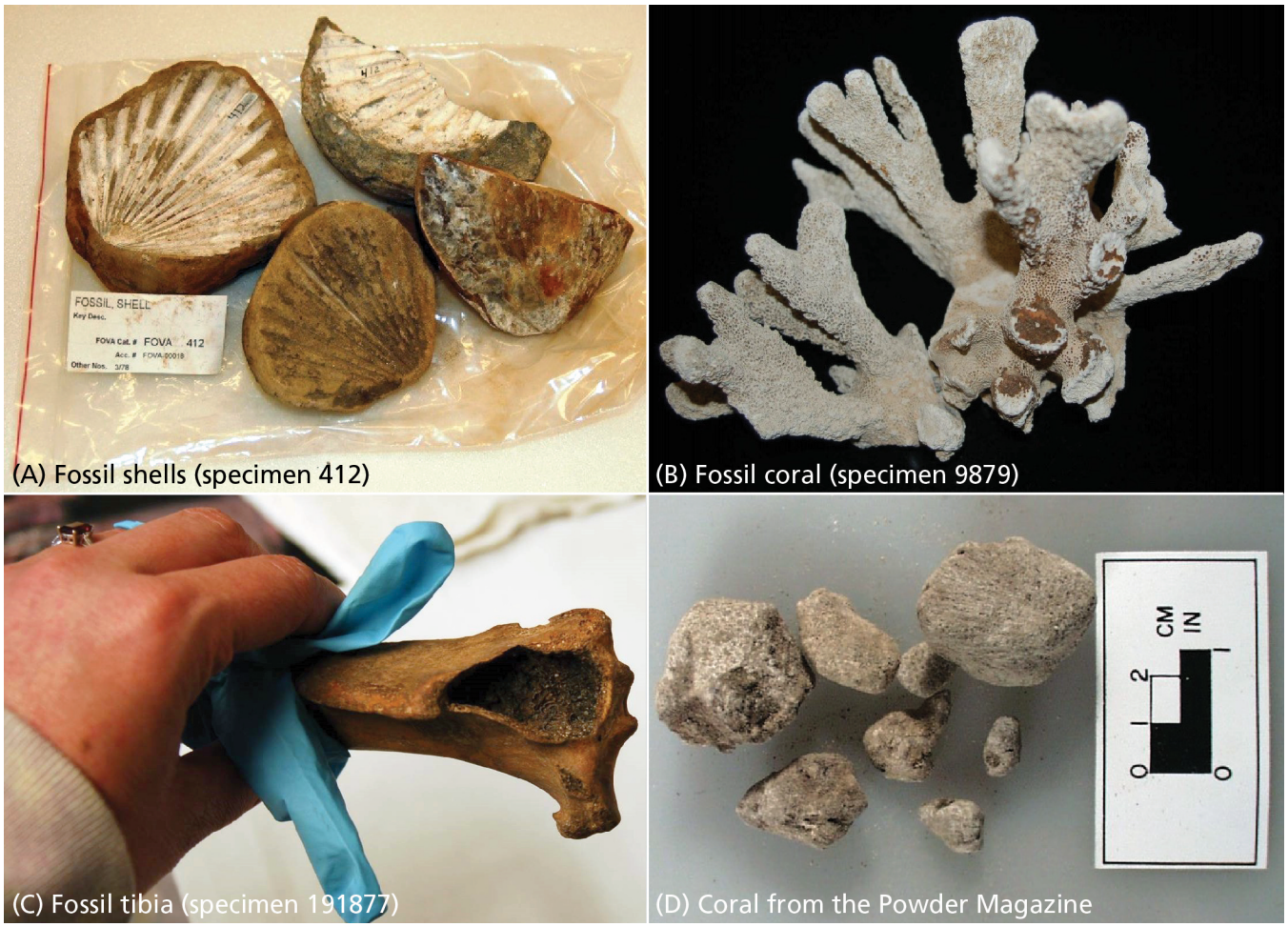


Figure 17. Photographs of fossils in the archeology collections at Fort Vancouver National Historic Site. Fossils come from the Columbia River alluvium (Qac) and artificial fill (Qaf). (A) Impressions of Patinopectin shells. (B) Fossil coral that may have belonged to an individual resident's personal collection. (C) A 23.5 cm (9.25 in) tibia fragment collected from Kanaka Village site in 1974. (D) Coral fragments collected from the foundation of the Powder Magazine, constructed in 1832. NPS photographs.

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.

Seismic Activity Hazards

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. Real-time earthquake data may be acquired on the PNSN website (https://pnsn.org/, accessed 01 April 2017) and from the USGS Earthquake Hazards Program, National Earthquake Information Center (NEIC) website (https://earthquake.usgs.gov/contactus/golden/neic.php, accessed 01 April 2017). In addition, the Oregon DOGAMI maintains an extensive list of earthquake-related topics including "Portland Metro Natural Hazards Publications" and "DOGAMI earthquake hazard maps" (http://www.oregongeology.org/sub/earthquakes/earthquakehome.htm, accessed 01 April 2017).

Slope Movement Hazards

Slope movements are a common type of geologic hazard—a natural or human-caused condition that may impact park resources, infrastructure, or visitor safety.

The Oregon DOGAMI provides a fact sheet on Oregon landslide hazards that illustrates slides, flows, spreads, and topples/falls, which are the common landslide types in Oregon, and identifies the following triggers for Oregon landslides: intense rainfall, rapid snow melt, freeze/thaw cycles, earthquakes, human activities, and a combination of these factors (http://www.oregongeology.org/pubs/fs/landslide-factsheet.pdf, accessed 01 April 2017). The fact sheet also notes signs of potential landslide problems, how to reduce the risks of landslides, and resources to access for additional information.

The Oregon DOGAMI also provides access to an interactive digital compilation of landslide inventory maps (http://www.oregongeology.org/slido/index.html, accessed 25 August 2017). The quality and spatial reliability of the maps vary, but they are useful for general planning purposes. Slope movements in the vicinity of the McLoughlin House unit have been characterized as "Pre-Historic (>150 yrs)." However, many small debris flows occurred in the Oregon City area in 1996 and 1997, and rockfall and other landslides occur in Oregon City during most winters (Madin 2009; Hofmeister 2000).

In the Geological Monitoring chapter about slope movements, Wieczorek and Snyder (2009) described five vital signs for understanding and monitoring slope movements: (1) types of landslide, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessment of landslide hazards and risks.

Volcano Hazards and Risk

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 slope movements. 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 CVO actively monitors all volcanic activity in the Pacific Northwest (https://volcanoes.usgs.gov/observatories/cvo/, accessed 28 March 2017). The Oregon DOGAMI website also provides information on volcanic activity including a "Mt. Hood Coordination Plan" developed by the Oregon Emergency Management and Washington Emergency Management Department in conjunction with local jurisdictions (http://www.oregongeology.org/sub/earthquakes/MtHood.htm, accessed 01 April 2017). The plan enhances hazard planning efforts and offers recommendations on Mt. Hood volcanic event preparedness, response, and recovery in order to minimize impacts of volcanic activity on people, property, the environment, and the economy of the Pacific Northwest.

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. Fort Vancouver National Historic Site management 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

Table 3. Regional geologic features and processes associated with Fort Vancouver National Historic Site.

Information extracted primarily from Evarts et al. (2009) and Madin (2009).

Feature	Processes
Alpine Glacial Features	The advance and retreat of alpine glaciers resulted in large outwash terraces. Some older terraces in the area may represent these alpine glacial deposits.
Dunes	East–west trending sand dunes (**Qff**) north of the historic site resulted from either strong easterly winds blowing through the Columbia Gorge (see Graham 2009) or from glacial Lake Missoula floodwaters channeled through Lacamas Lake trough (Richard Waitt, Cascades Volcano Observatory, geologist, written communication, 21 July 2017).
Coastal Features	Tidal influence from the Pacific Ocean reaches Bonneville Dam, 64 km (40 mi) east of Portland, Oregon, in the Columbia River Gorge. Tidal range at the historic site is 0.6–0.9 m (2–3 ft).
Willamette Falls	The cataract plummets over the Sentinel Bluffs Member of the Grande Ronde Basalt (**Tgsb**) and marks the contact between the Grande Ronde Basalt and the basalt of Ginkgo unit in the Frenchman Springs Member of the Wanapum Basalt (**Twfg**). Waterfalls signal a sharp change in a channel's slope, a feature known as a knickpoint. Willamette Falls may have originated as a result of past movement along the Bolton Fault and migrated upstream because of erosion. Graffiti from Joe Meek, who carved his name in the basalt in 1841, is still visible at the falls.
Faults	The northwest–southeast-trending Portland Hills, Oatfield, and Bolton faults cut the northwest–southeast-trending Portland Hills anticline between the Fort Vancouver and McLoughlin House units. The faults are mapped on the enclosed GRI GIS data.
Slope Movement (landslides)	Rainfall, earthquakes, and freeze/thaw processes have triggered landslides and other mass wasting in the Portland region. Regional landslides come in two general classes: (1) large, deep-seated, relatively coherent block slides, and (2) smaller, rapidly moving slides. Block slide or rotational slump features in **Qls** feature steep head scarps and hummocky topography. Slide mass thicknesses range from 6–24 m (20–79 ft). Old growth stumps up to 1.2 m (4 ft) in diameter stand upright on the surfaces of some slides, indicating at least centuries of stability. The GRI GIS data include location information for mass movements as mapped by Madin (2009).
Volcanic Features	Volcanic activity produced the thick basalt deposits associated with the Columbia River Basalt Group (~15 million years ago) and the Boring Volcanic Field rocks (~2.6 million years ago). Vents associated with the Boring Volcanic Field are located in the northeastern and southeastern corners of Madin's 2009 map of the Oregon City quadrangle and included in the GRI GIS data.
Features associated with Global Climate Change	Increases in intensity and frequency of rainfall may increase flooding. The Fort Vancouver unit borders the Columbia River and features associated with the river bank may change due to erosion caused by heightened tidal fluctuations and flooding.

Table 4. Geologic resource management issues associated with geologic units mapped within the Fort Vancouver and McLoughlin House units, Fort Vancouver National Historic Site.

Map Unit (symbol)	Geologic Resource Management Issue
Artificial Fill (Qaf)	**Flooding** (Fort Vancouver Unit) **Qaf** is mapped within the Columbia River floodplain and may be flooded.
Alluvium of Columbia River floodplain (Qac)	**Flooding** (Fort Vancouver Unit) The Pearson Field runway and terrace were flooded in 1948. Flooding also occurred in the winter of 1996. The floodplain, separated from the river by a natural levee, may flood because of groundwater seepage. In addition, a leaking utility system could cause flooding in the Hudson's Bay Company cemetery. The Oregon DOGAMI website contains information concerning flooding in Oregon, including risk assessments and channel migration analyses (http://www.oregongeology.org/flood/default.htm, accessed 01 April 2017).
Alluvium and Artificial Fill (Qac, Qaf)	**Inventory, Monitoring, and Protection of Paleontological Resources** (Fort Vancouver Unit) All paleontological resources are archived with the archeology collections. Fay et al. (2009) recommended that known paleontological resources be more fully examined and that the feasibility of cross-referencing paleontological items within the archeology collections be explored. Theresa Langford, (curator, Fort Vancouver National Historic Site, personal communication, 21 May 2018) noted that each specimen must be recorded in either the archeology or the paleontology database because "a single specimen cannot be classified as both archaeology and paleontology without creating duplicate records because we use unique catalog numbers." However, notes in the description field may be used to cross-reference specimens in the database. Future archeology excavations should include a paleontological survey. **Global Climate Change** (Fort Vancouver Unit) Rising sea level and an increase in rainfall may result in increased bank erosion and flooding in areas of alluvium (**Qac**) and artificial fill (**Qaf**).
Missoula flood deposits (Qff)	**Slope Movement and Infrastructure** (Fort Vancouver Unit) Terrace and flood deposits are well-drained and pose a minimal risk of failure. Boulders deposited by the ice age floods may interfere with construction and infrastructure maintenance. **Radon Exposure** (Fort Vancouver Unit) Long term exposure to elevated levels of radon increases the risk of lung cancer. The Environmental Protection Agency's (EPA) recommended maximum level of radon gas concentration is 4 picocuries per liter (pCi/L) (EPA 2013). Because radon is heavier-than-air, it may accumulate in poorly ventilated areas of the officers' quarters in Fort Vancouver. Although Officer's Row is located on adjacent Vancouver National Historic Site property, the level of radon at Fort Vancouver National Historic Site should be measured, monitored, and mitigated if levels are above EPA recommendations. Mitigation of radon gas is easily accomplished by installing ventilation systems. More information concerning radon is available from the EPA's radon website: http://www.epa.gov/radon.
Columbia River Basalt Group, Wanapum Basalt, Frenchman Springs Member, basalt of Ginkgo (Twfg)	**Slope Movement and Infrastructure** (McLoughlin House Unit) Cliff collapse may decrease the stability of the McLoughlin and Barclay houses. Singer Creek once flowed through the McLoughlin property, possibly following a zone of weakness, but has since been re-routed (fig. 18). The Barclay house is located a few feet from the bluff's edge but farther from Singer Creek than McLoughlin House. Obvious indicators of slope instability were not seen on the 2009 GRI field trip (see Graham 2009). For example, vegetation was well-established, there were no groundwater seeps, no debris at the base of the cliff, no fresh scarps, no vertical fractures in the dense basalt, tree trunks did not indicate downslope creep, and the McLoughlin House window frames were not displaced, which might indicate settling (fig. 19). Nevertheless, the concave topography of the bluff may be the result of slumping or collapse associated with Singer Creek's previous channel, and according to James O'Connor, yearly rockfall associated with cliffs of Ginkgo basalt are common elsewhere along Singer Hill Road, such as along Highway 99E near Willamette Falls (James O'Connor, US Geological Survey, hydrologist, written communication, 20 July 2017). The exceptional amount of rain that led to the 1996 flood event may have triggered slumping of Ginkgo basalt from the cliff below the McLoughlin House (see Graham 2009). Madin (2009) mapped a small slope movement approximately 60 m (200 ft) from the McLoughlin House unit located by Hofmeister (2000). That movement occurred as a "minor debris flow" during the 1996–1997 storms.



Figure 18. Photograph of Singer Creek in the McLoughlin House unit, Fort Vancouver National Historic Site. Once flowing through the middle of the property, the creek has been re-routed to the south of the property and contained within a concrete channel. Photograph by John Graham (Colorado State University).

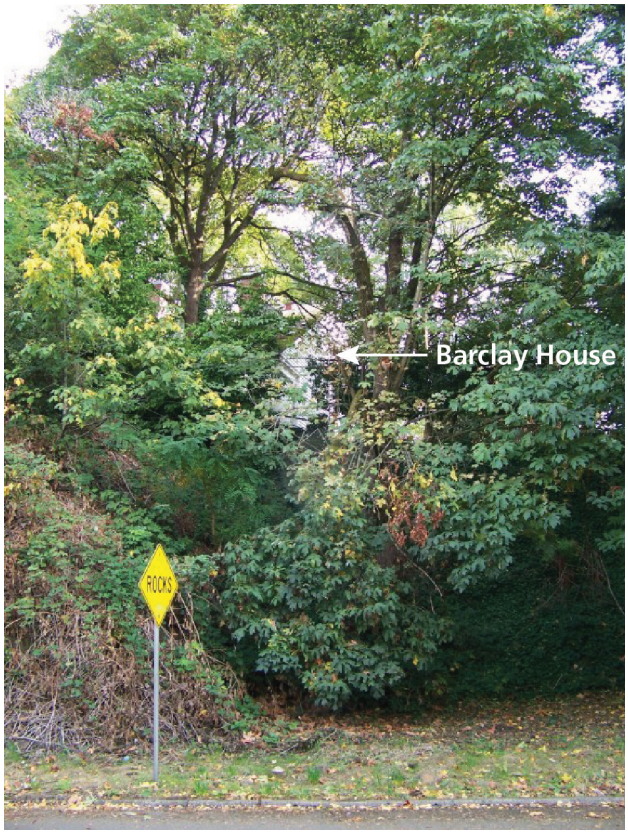


Figure 19. Photograph showing stability and instability indicators for the bluff behind the McLoughlin and Barclay houses.
Indicators of bluff stability include rooting from dense vegetation, a lack of denudation from previous slides, and tree trunks that do not list downslope. Rock slides, however, must have occurred in the past with enough regularity to warrant a sign. Note the proximity of the Barclay House to the edge of the bluff and the concave nature of the cliff, which would suggest past collapse. Photograph by John Graham (Colorado State University).

Table 5. Regional geologic hazards associated with Fort Vancouver National Historic Site.

Information extracted primarily from Evarts et al. (2009) and Madin (2009).

Features	Potential Regional Hazards
Faults	Movement on the three faults in the Portland area has been ongoing since the middle Miocene, but very low slip rates and recurrence intervals of tens of thousands of years suggest minimal hazard potential. The slip rate for the Portland Hills Fault is 0.075 mm/yr (0.003 in/yr); Bolton Fault slips at a rate of 0.011 mm/yr (0.0004 in/yr), for example (Madin 2009).
Earthquakes	Magnitude 6–7 earthquakes are possible, but according to Madin (2009, p. 43), are modest. The USGS suggests a relatively low probability for a major earthquake in the next 50 years (fig. 20). Most threats of shaking and subsequent liquefaction come from random local earthquakes and earthquakes generated by the offshore Cascadia Subduction Zone (fig. 4). Tsunamis would not impact the Fort Vancouver area, but liquefaction triggered by earthquakes may cause damage in low-lying areas in the Fort Vancouver unit. Because Fort Vancouver and the officers' quarters were constructed on terrace gravels away from the banks of the Columbia River, liquefaction effects may be minimal at the site. The Pacific Northwest Seismic Network (PNSN) continuously monitors seismic activity (http://www.pnsn.org/outreach/earthquakesources).
Slope Movement (landslides)	Block slides may cover tens of hectares and extend to depths of tens of meters. Indicators of recent slope movement include fresh scarps, open ground cracks, or tilted trees. Many older slides may have been triggered by rapidly receding glacial Lake Missoula floodwaters from saturated slopes. Intense rainfall events trigger smaller slides, which may cause significant damage. Increased frequency and intensity of rainfall events caused by global climate change may generate slope movement in the McLoughlin House unit area.
Volcanic Activity	Minimal risk. Rocky Butte, Powell Butte, Kelly Butte, and Mount Tabor, cinder cones that are part of the Boring Volcanic Field, are within Portland's city limits. The most recent eruptions from these volcanoes range from about 300,000 years ago (Mount Tabor) to 130,000 years ago (Rocky Butte). Eight volcanic vents are mapped on the Oregon City quadrangle (see GRI GIS data; Madin 2009). Currently, the Cascade Range to the east harbors most of the volcanic activity. The Cascades Volcano Observatory (CVO), which is part of the USGS Volcano Hazards Program, monitors volcanic activity in the Pacific Northwest (https://volcanoes.usgs.gov/observatories/cvo/). According to the CVO, all existing volcanic centers in the Boring Volcanic Field are extinct, but the Boring Volcanic Field may not be. However, the probability of an eruption in the Portland/Vancouver metro area is very low (https://volcanoes.usgs.gov/observatories/cvo/cvo_boring.html).
Issues associated with Global Climate Change	According to the Intergovernmental Panel on Climate Change (IPCC), human activities have caused over half of the observed increase in global average surface temperature from 1951 to 2010 (Stocker et al. 2013). As temperatures continue to increase, glaciers retreat and sea level rises. Fort Vancouver NHS is on the list of NPS units vulnerable to sea level rise (see "Coastal Features"). Although marine salinity in the Columbia River only extends to between Altoona and Skamokawa, Washington, roughly halfway between Longview and the coast, not to Portland, sea level rise caused by global climate change may alter the tidal range at the park and increase erosion along the banks of the Columbia River (Jay 1984; Jay et al. 2016). Rising sea level will alter river and groundwater levels. The Fort Vancouver complex is currently 5.5 m (18 ft) above mean sea level. Rising sea level may change the water chemistry in the Columbia River as far upstream as Longview, but is not expected to change the water chemistry of the channel adjacent to Fort Vancouver. See Beavers et al. (2016) for general guidance regarding coastal adaptation strategies. In the Pacific Northwest, average annual temperatures have risen about 0.7°C (1.3°F) since 1895, with some areas experiencing increases of 2°C (4°F). Average temperatures are expected to increase another 1.8°C to 5.4°C (3.3°–9.7°F) by 2100 (Mote et al. 2014). Warming is projected to exacerbate the demand for over-allocated water resources as snowpack decreases in the mountains, more flooding occurs in winter, and summer flows are reduced (Mote et al. 2014). The average April 1 snowpack in the Cascade Range, for example, has decreased by about 20% since 1950 (Mote et al. 2014). As approximately 70% of Oregon's electricity comes from hydropower, variability in water quantity and seasonal streamflow, combined with domestic, agricultural, and other industrial demands, may profoundly influence Oregon communities. Per the Oregon Climate Research Institute (2010), most of the more dramatic impacts of global warming will occur west of the Cascade Range and along Oregon's coast, but streamflow may also be affected, thereby influencing riparian habitats, incision rates, and cliff erosion. Additional potential impacts of global climate change are detailed in the references cited above. If, as projected, rainfall increases in the region, slumping or erosion may increase on Singer Hill, which may impact the McLoughlin House site. Increased precipitation may result in a shallower groundwater table beneath the floodplain in the historic site, potentially increasing groundwater flooding. NPS guidance for climate change adaptation of cultural resources is provided by Rockman et al. (2016).

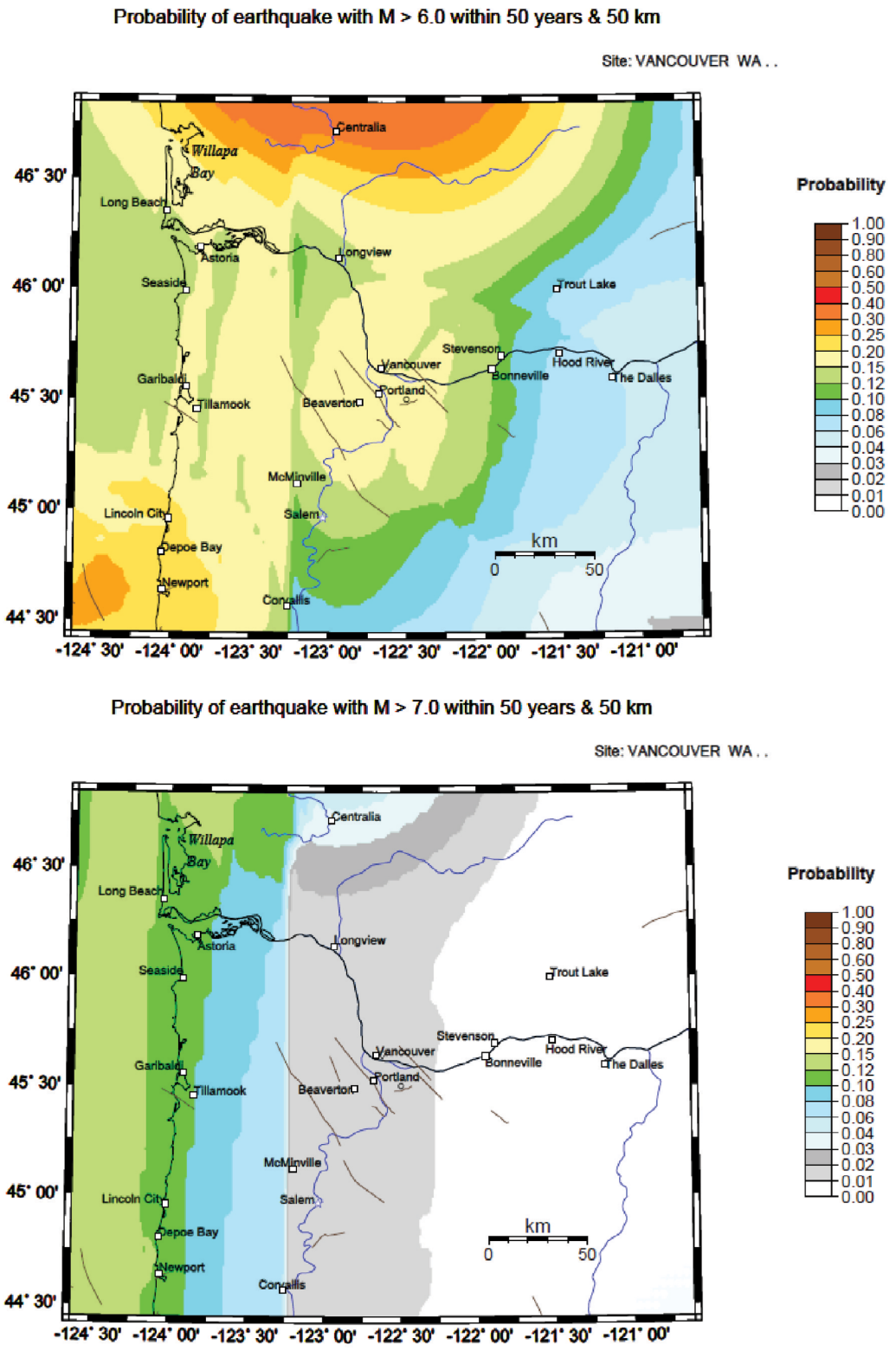


Figure 20. USGS earthquake probability maps for the Fort Vancouver National Historic Site region. In the upper map, the probability that either unit (yellow stars) will be affected by a magnitude 6.0 or greater earthquake by CE 2058 is 0.15–2.0. In the lower map, the probability ranges from 0.01 to 0.02 that an earthquake of magnitude 7.0 or greater will affect the historic site within the same time period. Earthquake probabilities are from USGS Open-File Report 08-1128 (Petersen et al. 2008), available at https://pubs.usgs.gov/of/2008/1128/pdf/OF08-1128_v1.1.pdf (accessed 28 March 2017).

Table 6. Summary of the geologic history associated with Fort Vancouver National Historic Site.

"MYA" refers to millions of years ago. Adapted from Evarts et al. (2009) and Madin (2009).

Epoch MYA	Geologic History
Holocene 0.01–0	20th century construction of dams and floodplain levees (map unit **Qaf**).
	Eruptions from Mt. Hood and Mt. St. Helens deposited lahars and volcaniclastic sediment in the Portland Basin.
	Rising sea level led to aggradation of the Columbia River's channel and floodplain (map unit **Qac**).
	Strong easterly winds, especially in winter, distributed loess (wind-blown silt) known as the Portland Hills Silt across most upland surfaces, including uplands close to the Columbia River and in the Portland Hills.
Pleistocene 0.016–0.012	Ice dams responsible for glacial Lake Missoula ruptured multiple times, resulting in cataclysmic floods that scoured the landscape of eastern Washington and sent flood waters careening through the Columbia River Gorge and into the Portland Basin (fig. 13; map unit **Qff**). The floods carved immense channels and constructed large gravel bars.
Pleistocene <0.58	The Columbia River incised sand and gravel deposits to form broad terraces in the Portland Basin.
Pliocene–Pleistocene 2.7–1.2	Volcanic eruptions formed the cinder cones and associated lava flows of the Boring Volcanic Field.
Pliocene 3.5–3	Basaltic lava flows and hyaloclastite deposits from the Cascade Range filled the Columbia River canyon. The Columbia River diverted to the north, and subsequent Quaternary incision carved the present western Columbia River Gorge.
Miocene–Pliocene 8–4	The Columbia River incised through Troutdale Formation (**Tt**) conglomerate, eventually reverting to a low-gradient, near-sea level stream and depositing the Springwater Formation and the upper Sandy River Mudstone (fig. 22)
	Coarse sandstone and conglomerate of the Troutdale Formation (**Tt**) transformed the Columbia River into a gravel-bed stream. Metamorphic and granitic cobbles and pebbles suggest an influx of sediment from sources far upstream.
Miocene 15–8	The Columbia River transported abundant sediment into the subsiding Portland Basin (fig. 22).
	About 14 million years ago, the Portland Hills anticline deflected the ancestral Columbia River to the north.
Miocene 16–15	Eruptions from vents in eastern Oregon and Washington produced the lava flows of the Columbia River Basalt Group (fig. 6). The Grande Ronde Basalt flowed into the broad Columbia River Valley that transected the Cascade Range. About 15.6 million to 15.3 million years ago, the basalt of Ginkgo, Frenchman Springs Member of the Wanapum Basalt, Columbia River Basalt Group (**Twfg**) erupted and now underlies the McLoughlin House unit.
Miocene 20	Portland Basin began to form, possibly as a broad syncline that developed parallel to the Portland Hills anticline (fig. 22). The ancestral Columbia River flowed along the synclinal axis.

Geologic History

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

Over 500 million years of nearly-continuous tectonic collisions, volcanic eruptions, fluctuating sea level, erosion, and deposition shaped the current west coast of North America. Mountain-building episodes (orogenies) resulted in mountain ranges extending from Alaska to Mexico. Fort Vancouver National Historic Site captures roughly 20 million years of this expansive West Coast geologic history that includes: (1) the development of the Portland Basin, (2) the eruption of vast quantities of basalt, (3) the evolution of the Columbia River, and (4) the influence of catastrophic ice age floods on the current landscape (table 6).

Tectonic Taffy and the Development of the Portland Basin

By the beginning of the Cenozoic Era 66 million years ago (fig. 5), the western margin of North America was colliding with the Farallon tectonic plate (fig. 21). The two tectonic plates converged 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 23.7 million years ago, the oblique convergence consumed the Farallon plate until it was left with two sections, the Juan de Fuca plate in the north and the Cocos plate south of the San Andreas Fault (fig. 21). The oblique collision also caused the northward moving Oregon Coast Range microplate to rotate clockwise, resulting in a right-lateral (dextral) shearing motion (Wells et al. 1998; Evarts et al. 2009a). About 20 million years ago, this complex movement began to stretch and pull apart the crust like taffy, opening the Portland Basin (fig. 22). The basin may have formed as a broad syncline (concave fold) parallel to the Portland Hills anticline (convex fold) (fig. 3; Evarts et al. 2009a).

Rivers of Fire: Columbia River Basalt Eruptions

Complex subduction (one tectonic plate sliding beneath another and into the upper mantle) 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. 4). During the middle Miocene, approximately 16 million years ago, rivers of basaltic lava poured from fissures that opened in the eastern Oregon crust (fig. 6). Low viscosity basaltic (lower silica content) and andesitic (medium silica content) 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. The Columbia River Basalt Group includes the Grande Ronde Basalt (geologic map units **Tgsb** and **Tgww**) and the Wanapum Basalt (**Twfs**, **Twfg**), which flowed into the Portland Basin via the ancestral Columbia River (fig. 22). Volcanic ash and lava inundated the Columbia Basin and Fort Vancouver region, as well as much of present-day eastern Oregon, including John Day Fossil Beds National Monument (see Graham 2014b).

Debate on the origin of the Columbia River basalts continues. A mantle plume hypothesis suggests that the outpouring of basalt was caused by the same 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). 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).

During the last half of the Miocene, the Columbia River transported as much as 200 m (660 ft) of fine-grained fluvial and lacustrine sediments, tuffaceous (made up of volcanic ash) sandstone and siltstone, claystone, lignite, and local pebble conglomerate of the Sandy River Mudstone into the subsiding Portland Basin (fig. 22; Trimble 1963; Evarts et al. 2009a). Sedimentary features in the Sandy River Mudstone record a low-gradient Columbia River. Sediments were deposited near sea level although there is no evidence to suggest that a marine estuary extended into the Portland Basin. Volcanic activity in southern Washington was weak, but eruptions of andesitic volcanoes to the southeast, in the



Figure 21. Paleogeographic maps showing the evolution of the Cascadia Subduction Zone. 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 Fort Vancouver National Historic Site. Annotations by Trista Thornberry-Ehrlich (Colorado State University). Base paleogeographic maps by Ron Blakey (Colorado Plateau Geosystems, Inc.), available at http://cpgeosystems.com/index.html (accessed 27 November 2016).

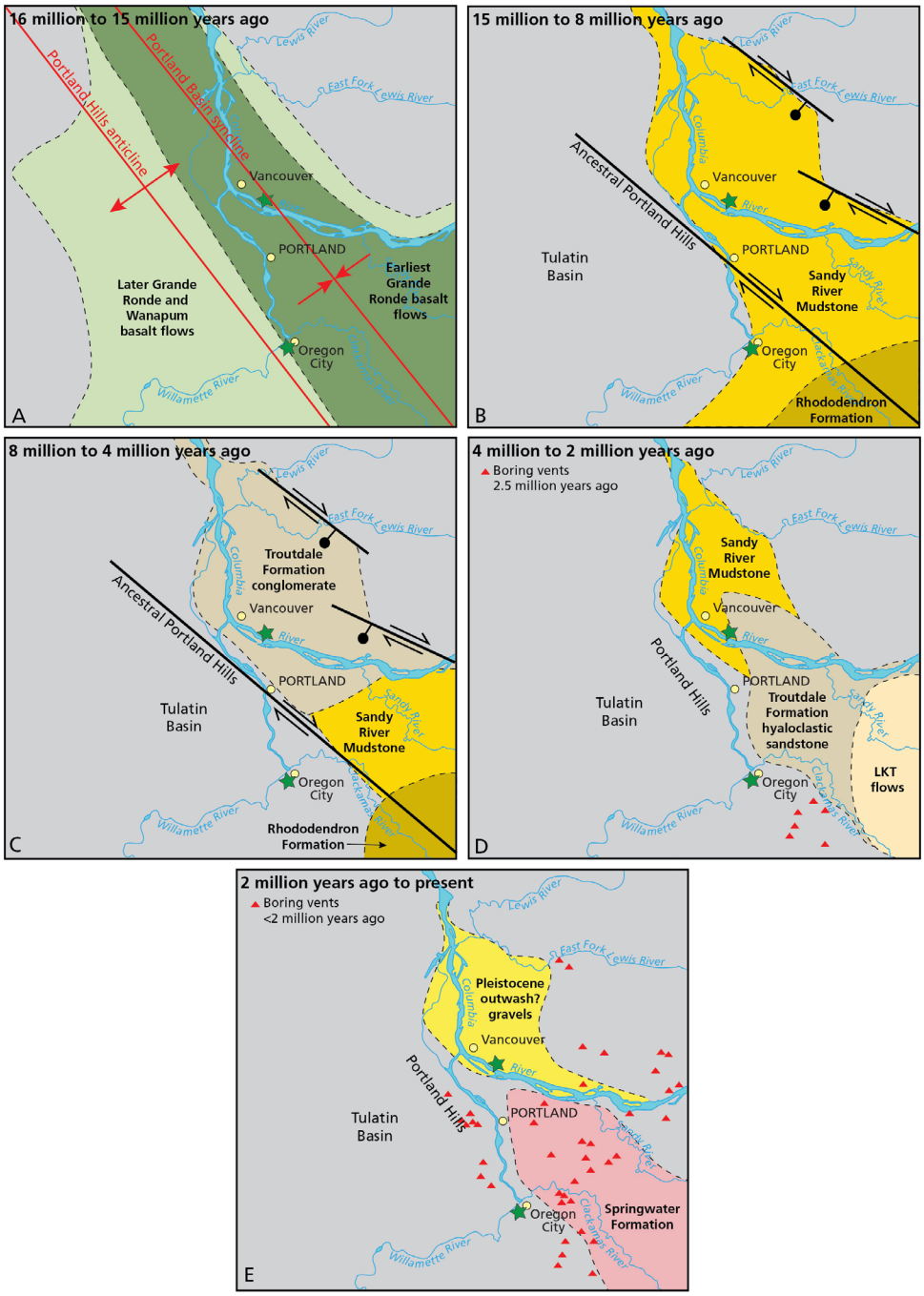


Figure 22. The evolution of the Portland Basin.
(A) Initiation of the Portland Basin as a syncline in the Miocene. Grande Ronde Basalt (Tgsb, Tgww) flows are diverted to the north by the Portland Hills anticline. (B) Subsidence continues and northwest-striking fault zones develop. The ancestral Columbia River deposits the Sandy River Mudstone on a broad floodplain. (C) Deposition of the Troutdale Formation (Tt) conglomerate. (D) Hyaloclastite sandstone in the Troutdale Formation is deposited in the eastern Portland Basin and subsequent incision forms the modern Columbia River Gorge. Renewed volcanism initiates the Boring Volcanic Field about 2.6 million years ago. (E) Pleistocene ice age outwash gravels are deposited in the north; the Columbia River erodes these deposits, establishing its present course; Boring Volcanic Field eruptions resume at 1.6 million years ago, spreading northward (the initial Boring Volcanic Field eruptions plotted in D are replicated in E to show the full extent of the field); and outburst floods from glacial Lake Missoula deposit sediment and sculpt terrain below 120 m (390 ft) above sea level. Graphic redrafted by Trista Thornberry-Ehrlich (Colorado State University) after Evarts et al. (2009, figure 3).

northern Oregon Cascades, fed debris flows and fluvial deposits that formed the thick, northward-sloping volcaniclastic apron of the Rhododendron Formation (fig. 22). Near the end of the Miocene, over 200 m (660 ft) of lower Troutdale Formation (**Tt**) sandstone and conglomerate filled a narrow paleocanyon cut into the Grande Ronde Basalt, north of the present Columbia River. Although movement on the Bolton Fault is difficult to pinpoint with a great deal of accuracy, movement may have occurred prior to the deposition of the Troutdale Formation (Madin 2009).

Carving the Columbia River Gorge

A high-energy, braided river system carried abundant sand, pebbles, and cobbles through this narrow paleocanyon and into the Portland Basin from eastern Oregon, eastern Washington, and Idaho (Evarts et al. 2009a). In the early Pliocene, the Columbia River incised through the thick gravel of the Troutdale Formation and entered the Portland Basin through a canyon south of the modern Columbia River Gorge (Tolan and Beeson 1984; Evarts et al. 2009a). In time, the river reverted to a near-sea level stream, depositing the fine-grained sediment and early Pliocene fossil plant material of the upper Sandy River Mudstone (fig. 22; Trimble 1963; Tolan and Beeson 1984; Evarts et al. 2009a).

Renewed volcanic activity in the Cascade Range approximately 3.5 million years ago once again inundated the Portland Basin with voluminous lava flows and large quantities of hyaloclastite (hydrated tuff-like breccia rich in black volcanic glass), which built a large fan where the river entered the Portland Basin (Evarts and O'Connor 2008; Evarts et al. 2009a). When lava flows and sedimentary deposits completely filled the Columbia River canyon where it cut through the western Cascade Range, the river channel diverted to the north. Quaternary incision would eventually carve the present western Columbia River Gorge (Tolan and Beeson 1984). Beginning roughly 2.6 million years ago, volcanic eruptions formed the cinder cones and associated lava flows of the Boring Volcanic Field (fig. 22). According to the CVO, the Boring Volcanic Field consists of over 80 small volcanic vents and lava flows in the Portland-Vancouver metropolitan area (Evarts et al. 2009b). Younger sedimentary deposits resulting from the glacial Lake Missoula ice age floods probably bury additional volcanic centers. Beacon Rock, which erupted as a large cinder cone about 57,000 years ago, is the youngest volcano in the Boring Volcanic Field. About 15,000 years ago, the Missoula Floods stripped away the tephra (cinder) that surrounded the volcano, leaving only the central plug (fig. 23). Although all existing Boring Volcanic centers are extinct, the Boring Volcanic Field remains potentially active (Evarts et al. 2009a).

Colossal Glacial Floods Alter the Landscape

The landscape in the Fort Vancouver National Historic Site area has been shaped by both fire and ice. 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. 13). 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). Over a period of 2,000 to 3,000 years, the Purcell Trench Lobe of the Cordilleran Ice Sheet periodically blocked the Clark Fork of the Columbia River in Idaho, forming ice dams with heights of up to 760 m (2,500 ft) and widths of over 48 km (30 mi). At its maximum, probably about 18,000 calendar years (15,000 radiocarbon years) before present, the Missoula Lake dam contained up to 210 km^3 (50 mi^3) of ice (Booth et al. 2004; Allen et al. 2009).

How the ice dams failed remains a matter of conjecture. Water may have overtopped the dams, causing them to break. Subglacial tunneling in the ice, which is common in glaciers, may have caused the dams to fail. Subglacial tunnels would have formed once the lake level rose to a critical level of ~600 m (~2,000 ft), causing the glacier bed at the seal to become buoyant and water to flow beneath the dam. The subglacial tunnels would have grown exponentially, resulting in catastrophic discharge (Waitt 1985). Another possibility was exemplified in Iceland in 1996, when increased pressure at the bottom of an ice dam lowered the freezing point of lake water until the dam could no longer support its pressure. The dam failed, triggering a jökulhlaup, an Icelandic term for a glacial outburst flood (Roberts et al. 2002; Clague et al. 2003). Once a glacial Lake Missoula ice dam failed, catastrophic floods swept across eastern Washington, through the Columbia Gorge, into the Portland Basin, and out to sea, leaving behind the extraordinary features that still dominate the landscape (fig.15). Some of the Missoula Flood deposits (**Qff**) are mapped within the Fort Vancouver unit. Missoula Flood deposits (**Qff**) have also been mapped in the valley bottoms east of the McLoughlin House unit (GRD GIS map; Madin 2009).

The Modern Landscape

Volcanic activity and earthquakes associated with the Cascadia Subduction Zone (fig. 4) continue to modify the Portland Basin. About 1,500 years before present and again 200 years ago, the Sandy River served as a



Figure 23. Photograph of Beacon Rock (Washington), which is part of the Boring Volcanic Field. The Missoula Floods removed all but the central core of this cinder cone about 15,000 years ago. Note the cars and building in the lower left corner of the photograph for scale. USGS photograph, available at https://volcanoes.usgs.gov/observatories/cvo/cvo_boring.html (accessed 02 April 2017).

conduit into the eastern Portland Basin for lahars and abundant volcaniclastic sand and gravel derived from Mount Hood eruptions. Lewis and Clark named the Sandy River because of its abundant sand following eruptions in the 1780s. The Lewis River transported lahars and sediment from Mount St. Helens into the northern part of the Portland Basin, especially during eruptions 2,500 years and 500 years before present.

Approximately 13,000 years before present, near the end of the Pleistocene ice ages, the Columbia River was 113 m (370 ft) below present sea level. In the Portland Basin, 100 m (330 ft) of sand and silt filled a late Pleistocene paleochannel that is now buried below the modern Columbia River floodplain. The modern floodplain consists of unconsolidated sand, silt, and clay (**Qac**). Since the end of the last glacial epoch, sea level has been rising, resulting in aggradation of the Columbia River's channel and floodplain.

In the Fort Vancouver unit, floodplain deposits (**Qac**) were used by the Hudson's Bay Company to grow crops, and the gravel and boulder bars formed by Missoula Flood deposits (**Qff**) provided a location for the fort away from potential flooding of the Columbia River. Over the years, unconsolidated deposits have been used as fill for highway and railroad beds, levees, small dams, culverts, and other cultural uses (**Qaf**).

Accelerated sea level rise due to accelerated global climate change will increase as ocean waters warm and expand and ice melts, critically affecting coastal habitats in the Pacific Northwest. Results from global climate change that may directly impact Fort Vancouver National Historic Site include aggradation of the Columbia River, fluctuating river and groundwater levels, increased flooding of the Fort Vancouver unit, and increase slumping and erosion caused by intense rainfall events, which may destabilize the bluff behind the McLoughlin House unit.

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 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 geologic map for the Fort Vancouver unit and a bedrock geologic map for the McLoughlin House unit for Fort Vancouver National Historic Site.

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 fova_geology.pdf. The GRI team used the following sources to produce the GRI GIS data set for Fort Vancouver National Historic Site. These sources also provided information for this report.

- McLoughlin House unit (Oregon City quadrangle "ORCI" data layers; table 7): Madin (2009)
- Fort Vancouver unit (table 8): Cannon (2011)

GRI GIS Data

The GRI team standardizes map deliverables by using a data model. The GRI GIS data for Fort Vancouver National Historic Site was compiled using data model version 2.1, which is available is available at http://go.nps.gov/gridatamodel. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI Geologic Maps website, http://go.nps.gov/geomaps, provides more information about the program's map products.

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

The following components are part of the data set:

- A GIS readme file (fova_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information.
- Data in ESRI geodatabase GIS format;
- Layer files with feature symbology (tables 7 and 8);
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information document (fova_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross sections, and figures;
- ESRI map documents (fova_geology.mxd; orci_geology.mxd) that display the GRI GIS data; and
- Versions of the data viewable in Google Earth (fova_geology.kmz, orci_geology.kmz; tables 7 and 8).

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 (tables 7 and 8). Geographic information and selected park features have been added to the poster. Digital elevation data and added geographic information are not included in the GRI GIS data, but are available online from a variety of sources. Contact GRI for assistance locating these data.

Use Constraints

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

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

Table 7. GRI GIS data layers for the McLoughlin House unit of Fort Vancouver National Historic Site (orci_geology.mxd; orci_geology.kmz).

Data Layer	On Poster?	Google Earth Layer?
Geologic Cross Section Lines	Yes	No
Geologic Attitude Observation Localities (strike and dip)	No	No
Geologic Observation Localities	No	No
Geologic Sample Localities (mineralogical/chemical samples)	No	No
Wells and Boreholes	No	No
Hazard Point Features (small mass movements)	Yes	No
Volcanic Point Features (vents)	Yes	No
Map Symbology (fault symbols)	Yes	No
Faults	Yes	Yes
Geologic Contacts	Yes	Yes
Geologic Units	Yes	Yes

Table 8. GRI GIS data layers for the Fort Vancouver unit of Fort Vancouver National Historic Site (fova_geology.mxd; fova_geology.kmz).

Data Layer	On Poster?	Google Earth Layer?
Geologic Cross Section Lines	Yes	No
Cross Section Wells	No	No
Artificial Fill Contacts	Yes	Yes
Artificial Fill	Yes	Yes
Geologic Contacts	Yes	Yes
Geologic Units	Yes	Yes

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

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Additional References

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

Geology of National Park Service Areas

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

NPS Resource Management Guidance and Documents

- Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html.
- 1998 National parks omnibus management act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf.
- NPS-75: Natural resource inventory and monitoring guideline: 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 DOGAMI: http://www.oregongeology.org/sub/default.htm.
- Washington State Department of Natural Resources: Geology and Earth Resources: http://www.dnr.wa.gov/geology.
- USGS: 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/.

USGS 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 24 November 2009. Discussions during this meeting supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://go.nps.gov/gripubs.

Name	Affiliation	Position
Cromwell, Bob	NPS Fort Vancouver National Historic Site	Historical Archeologist
Davis, Marsha	NPS Pacific Northwest Regional Office	Geologist
Graham, John	Colorado State University	Geologist, GRI Report Writer
Heise, Bruce	NPS Geological Resources Division	Geologist, GRI Program Coordinator
Mack, Gregory	NPS Pacific Northwest Regional Office	Geologist, GIS Specialist
O'Connor, James	USGS	Hydrologist

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).

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

NPS 389/150823, March 2019

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