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Whitman Mission National Historic Site

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2014/839

ON THE COVER

View of Memorial Hill. Memorial Hill is comprised of rhythmites, layered deposits from Glacial Lake Missoula floodwater ponded behind Wallula Gap. The Whitman Memorial obelisk was erected atop the hill in 1897. Photograph by user "Patricedward," used under the Creative Commons Attribution-ShareAlike 3.0 Unported License (CC BY SA 3.0). Available at http://commons.wikimedia.org/wiki/File:Whitman_National_Monument.JPG (accessed 22 August 2013).

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Columbia River basalt in Palouse Canyon, downstream from Palouse Falls on the Palouse River in southeastern Washington, about 70 km (43 mi) northeast of Whitman Mission National Historic Site. The photograph illustrates the exceptional thickness of Miocene basalt. Public domain photograph available at http://en.wikipedia.org/wiki/File:Palouse-Canyon-Washington-State.jpg (accessed 29 July 2013).

Whitman Mission National Historic Site

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2014/839

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

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

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Executive Summary

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI. This report synthesizes discussions from a scoping meeting for Whitman Mission National Historic Site (Washington) on 8 March 2004, which was held by the Geologic Resources Division to determine geologic resources, the status of geologic mapping, and geologic resource management issues and needs. It is a companion document to previously completed GRI digital geologic map data.

Authorized as Whitman National Monument in 1936, 100 years after Marcus Whitman built his first house on the banks of the Walla Walla River, Whitman Mission National Historic Site (re-designated in 1963) commemorates the Whitman Mission and the opening of the Oregon Trail in the Pacific Northwest. Whitman's memorial is located on a steep hill surrounded by the floodplain of the Walla Walla River and Mill Creek. The site contains a restored mill pond and creek, an apple orchard, and historical sites such as the Mission House site, blacksmith shop, and grist mill.

As part of the Columbia Basin physiographic province, Whitman Mission National Historic Site and its immediate surroundings preserve the remains of one of the largest continental-flood basalt eruptions ever to occur in the Western Hemisphere. Between 17 million and 6 million years ago, basaltic magma poured from fissures and vents that cracked the crust in the region of present-day Oregon, Washington, and Idaho and flooded about 160,000 km^2 (63,000 mi^2) of the Columbia Plateau, eventually covering an area about the size of Wisconsin. By the time the eruptions stopped, up to 4,000 m (13,000 ft) of basalt flows covered the Columbia Basin. Remnants of this fiery episode in Earth's history lie approximately 160 m (524 ft) below the surface at Whitman Mission National Historic Site.

This region of fire was transformed to a region of ice during the Pleistocene ice age glaciations. Millions of years after basalt blanketed the landscape, the Cordilleran Ice Sheet advanced into the region of present-day Washington from the north. Glaciers pulverized bedrock into fine particles of silt, which were distributed throughout the Columbia Basin by the Missoula floods, wind storms, and the ancestral Columbia River drainage system. This wind-transported silt, referred to as loess, and alluvial silt are largely responsible for the productivity of agricultural land that encouraged Marcus Whitman to put down roots in the Walla Walla Valley.

The glaciers were also the sources of the most cataclysmic flood events ever recorded in North America. At the present-day Idaho–Montana border, a lobe of the Cordilleran Ice Sheet blocked the Clark Fork River, forming an ice dam and creating Glacial Lake Missoula, a reservoir containing up to 2,100 km^3 (500 mi^3) of water, about half the volume of Lake Michigan. When the ice dam failed, a towering mass of ice, water, mud, and debris roared across the region of present-day Idaho and the Columbia Basin until it was abruptly slowed by Wallula Gap, west of the current location of Whitman Mission National Historic Site. Floodwaters accumulated behind the constriction and sediment settled out of the water column in the quiet waters. Coarse sand and pebbles settled out first, followed by finer-grained silt and clay. This cycle was repeated at least 40 times, with ice dams forming and failing and catastrophic floods eroding gigantic channels in the underlying basalt. The last series of floods occurred approximately 18,000 to 15,000 years ago. Beneath the grassy slopes of Memorial Hill, the records of these cycles of sedimentation, known as rhythmites, document these stupendous flood events.

Basalts and rhythmites are two feature types that record the geologic history of Whitman Mission National Historic Site. Geologic features and processes of particular significance for resource management at the historic site include:

- Pleistocene rhythmites (Touchet Beds). Deposited in the quieter floodwaters of the colossal Lake Missoula floods, the rhythmically bedded sand and silt of the Touchet Beds provide evidence for multiple outburst floods. Many of these deposits have been eroded by fluvial processes since the Pleistocene, but rhythmites form the hill at Whitman Mission National Historic Site.
- Holocene alluvium. In contrast to the turbulence of the extraordinary Glacial Lake Missoula floods, the Walla Walla River, Mill Creek, and their tributaries rather calmly spread accumulations of clay, silt, fine sand, and pebbles (alluvium) across the Walla Walla Valley during the past 11,700 years, called the Holocene Epoch. At Whitman Mission National Historic Site, the restored Doan Creek provides an excellent example of the processes and features associated with a meandering stream.
- Loess. Transported by wind, loess forms an approximately 1-m- (3-ft-) thick layer on the hill at Whitman Mission National Historic Site. The loess-rich soil supports a variety of crops and was a main

feature attracting Marcus Whitman to Walla Walla Valley.

- Columbia River flood basalts. The few exposures of these basalts in the northwestern corner of the accompanying digital map are parts of lava flows that occurred between 15.5 million and 14.5 million years ago. These flows are part of the Columbia River Basalt Group, which represents one of the largest basaltic lava floods ever documented.
- Faults and folds. A broad syncline (concave-upward fold) and several faults have been mapped in the subsurface of the Walla Walla Valley. General north–south compression of the land in present-day southeastern Washington has generated northwest–southeast- and northeast–southwest-trending strike-slip faults that have been active before, during, and after the eruption of the Columbia River basalts. Some of the faults act as groundwater barriers.

Geologic issues that may be of particular significance for resource management at Whitman Mission National Historic Site include:

- Flooding. The Whitmans moved their first home because it was susceptible to flooding in its original location. Until 1931, major flooding on Mill Creek caused significant damage in Walla Walla and surrounding areas. A US Army Corps of Engineers project completed in 1942 protected the city from potentially devastating floods in 1964 and 1996. As part of the project, fish ladders were installed to provide fish passage. A projected increase in winter and early-spring streamflow due to global climate change may increase flooding potential. Combined with Chinook weather conditions and the narrowness of canyons in the surrounding mountains, these changing conditions may produce more intense flood events in the Walla Walla Valley, which may impact Whitman Mission National Historic Site.
- Seismic activity (earthquakes). Although earthquakes occur relatively frequently in western Washington, the last significant earthquake to impact the Whitman Mission region occurred in 1936, when a magnitude 5.75 earthquake centered near the Washington–Oregon border shook buildings and cracked the ground. Because north–south tectonic compression continues to affect the Columbia Basin, however, earthquakes remain a potential hazard in Walla Walla Valley.
- Doan Creek restoration. In 2005, park staff began restoring the channel of Doan Creek. Today, the creek contains features such as meander bends, pools, and riffles that simulate natural stream conditions, and it provides ideal habitat for fish, especially the threatened/endangered steelhead and salmon.
- Geothermal energy development. Walla Walla Valley and Whitman Mission National Historic Site are located in a low-temperature geothermal resource area characterized by thermal waters with temperatures of at least 20°C (68°F). Heat flow gradients and shallow drilling may support future geothermal energy development in the valley, but its effects on the park have not been evaluated.

This GRI report was written for resource managers to assist in science-based decision making. It may also be useful for interpretation. The report was prepared using available geologic information, and the NPS Geologic Resources Division conducted no new fieldwork in association with its preparation. Sections of the report discuss distinctive geologic features and processes within Whitman Mission National Historic Site, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the GRI geologic map data. A poster (in pocket) illustrates these data. The Map Unit Properties Table (in pocket) summarizes report content for each geologic map unit.

Products and Acknowledgments

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

GRI Products

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

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

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

Additional information regarding the GRI, including contact information, is available at: http://www.nature.nps.gov/geology/inventory/. The current status and projected completion dates of products are at: http://www.nature.nps.gov/geology/GRI_DB/Scoping/Quick_Status.aspx.

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Author

John P. Graham (Colorado State University)

Review

Robert Carson (Whitman College)
Jason Kenworthy (NPS Geologic Resources Division)

Editing

Jennifer Piehl (Wright Science Right)

Source Map

R. E. Derkey, D. F. Stradling, K. A. Lindsey, and T. L. Tolan (Washington State Division of Geology and Earth Resources)

GRI Digital Geologic Data Production

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

GRI Map Poster Design

Derek Witt (Colorado State University)
Georgia Hybels (NPS Geologic Resources Division)
Jason Kenworthy (NPS Geologic Resources Division)

GRI Map Poster Review

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

Geologic Setting and Significance

This section describes the regional geologic setting of Whitman Mission National Historic Site, and summarizes connections between geologic resources and other park resources and stories.

Park Setting

Whitman Mission National Historic Site is located approximately 4 km (7 mi) west of Walla Walla in southeastern Washington (fig. 1). The park's elevation ranges from 187 m (615 ft) on the relatively flat floodplain to 221 m (724 ft) above sea level at the top of Memorial Hill, where the prominent obelisk memorial to the Whitmans stands (see front cover). Annual precipitation averages 48 cm (19 in), with 43 cm (17 in) of snow during winter months. Maximum monthly temperatures range from 4.17°C (39.5°F) in January to 31.8°C (89.2°F) in July (Bell and Hinson 2009).

Mill Creek and the restored Doan Creek meander through the park (fig. 1). Maples, sycamores, elms, locusts, ash, sumac, wild rose, and flowering dogwood are among the various trees and shrubs that add beauty and shade to the park grounds. Remnants of a previous channel of the Walla Walla River remain visible in the southern part of the park's 56.06 ha (138.53 ac).

Authorized as Whitman National Monument in 1936 and re-designated Whitman Mission National Historic Site in 1963, the park commemorates the Whitman Mission, the opening of the Oregon Trail, and the challenges of coexistence faced by pioneers and the native Cayuse Indians. In 1836, Dr. Whitman and his wife, Narcissa, established the Whitman Mission at Waiilatpu, near the Walla Walla River. From 1843 to 1847, the mission served as an important stop along the Oregon Trail. The Whitmans were missionaries who attempted to impose Christianity and sedentary farming on the nomadic Cayuse Indians.

With the opening of the Oregon Territory, increasing numbers of immigrants began to arrive in the region, and conflict between them and the Cayuse Indians increased. In 1847, a measles epidemic killed about half of the Cayuse tribe. The Cayuse blamed the immigrants for bringing the disease and Dr. Whitman for not curing the sick. On 29 November 1847, a band of Cayuse and Umatilla Indians attacked the mission, killing Marcus

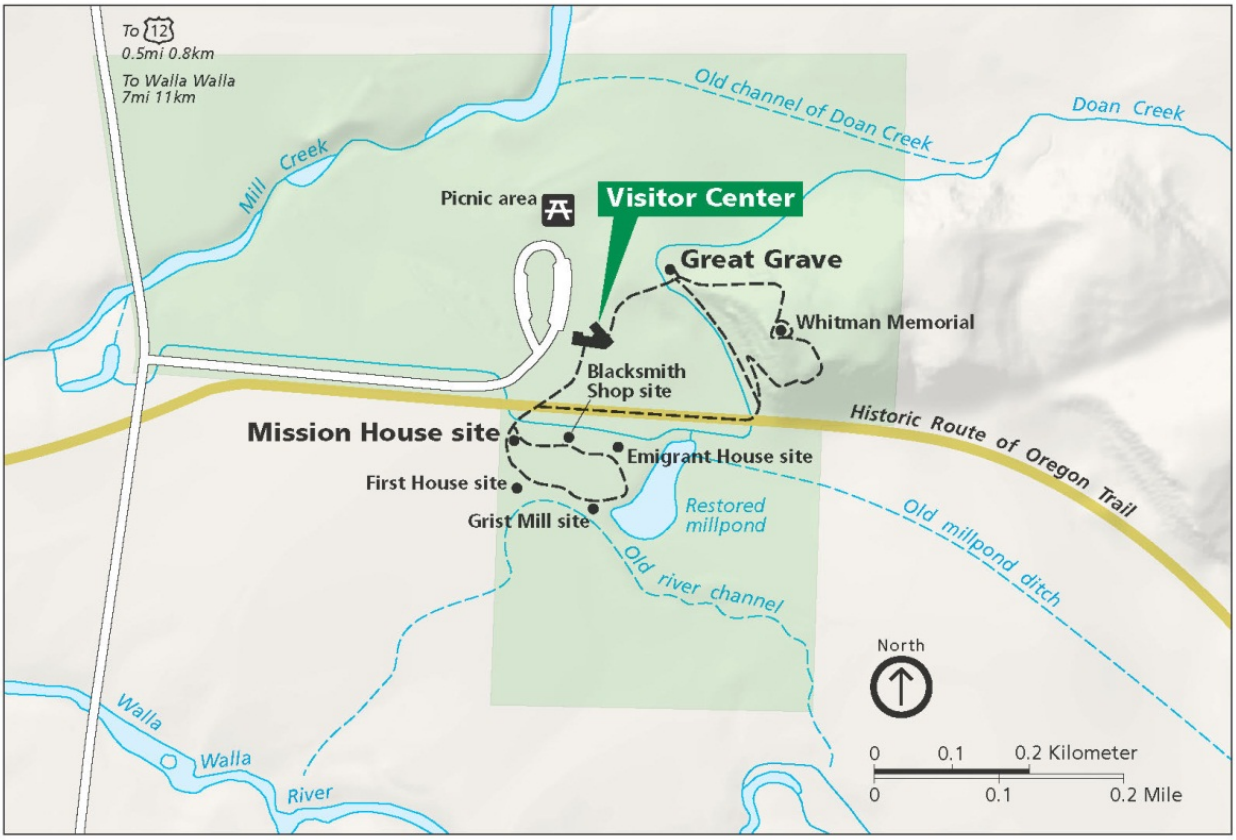

Figure 1. Map of Whitman Mission National Historic Site. The restored Doan Creek channel follows the "Old channel" indicated on this map. NPS map, available at http://www.nps.gov/hfc/cfm/carto-detail.cfm?Alpha=WHMI (accessed 19 July 2013).

Figure 2. Great Grave. The Whitmans and others slain at the site were buried in a grave at the base of Memorial Hill. Vermont marble was utilized to construct the grave marker and mausoleum. National Park Service photograph, available at http://commons.wikimedia.org/wiki/File:Whitman_Mission_Grave_WA_NPS.jpg (accessed 13 April 2014).

and Narcissa Whitman and 13 other men (fig. 2). They took 54 women and children captive and held them for ransom.

The ensuing Cayuse War between the Indians and the United States Government lasted until 1855, when the Cayuse were forced to cede most of their tribal lands and were relegated to the Confederated Tribes of the Umatilla Indian Reservation at the base of the Blue Mountains. The obelisk memorializing the Whitmans was erected in 1897.

Geologic Setting

Whitman Mission National Historic Site is located in the Columbia Basin (also known as the Columbia Plateau), a vast physiographic province of similar rocks, landforms, soil, climate, and vegetation that encompasses 36% of the state of Washington, as well as parts of Oregon and Idaho (fig. 3). Characterized by incised rivers and extensive plateaus, soils of windblown silt (referred to as loess), and sagebrush and short-grass prairie, the Columbia Basin is underlain by a thick sequence of Miocene-aged (fig. 4) Columbia River Basalt Group rocks (see inside cover) (Carson and Pogue 1996). Between 17 million and 6 million years ago (in the late Miocene and early Pliocene), numerous lava flows poured from fissures and volcanic vents that split the Columbia Plateau, flooding about 160,000 km^2 (63,000 mi^2; an area about the size of Wisconsin) of the Pacific Northwest with about 174,000 km^3 (41,800 mi^3) of basaltic magma (Barry et al. 2013; Baski 2013; Reidel and Tolan 2013a).

Three small exposures of the Frenchman Springs Member of the Wanapum Basalt Formation (geologic map unit MIvwfs), which belongs to the Columbia River Basalt Group, are the oldest rocks appearing on the accompanying digital map (fig. 5). These exposures can

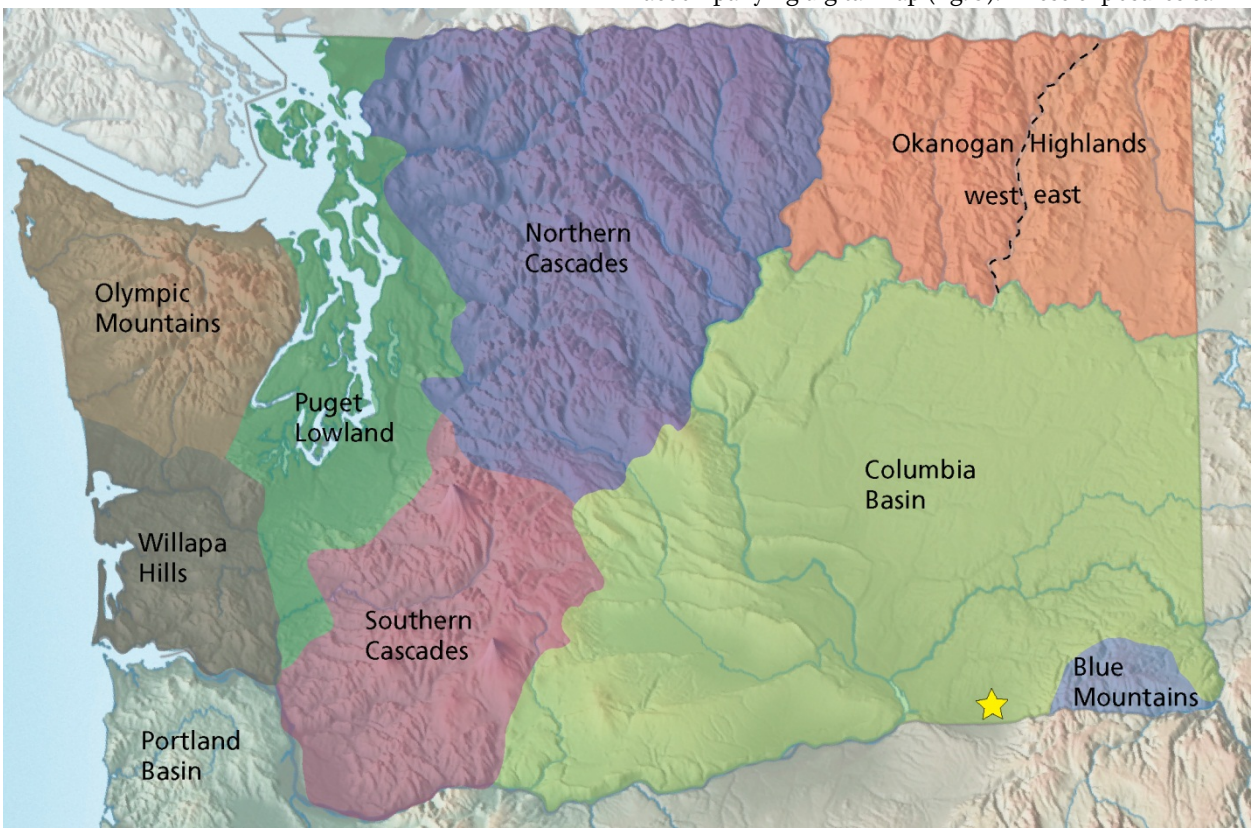

Figure 3. Physiographic provinces of Washington. Whitman Mission National Historic Site (yellow star) is located in the Columbia Basin. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after a Washington State Department of Natural Resources diagram, available at http://www.dnr.wa.gov/ResearchScience/Topics/GeologyofWashington/Pages/geolofwa.aspx (accessed 24 July 2013). Shaded relief base map by Tom Patterson (National Park Service), available at http://www.shadedrelief.com/physical/index.html (accessed 24 July 2013).

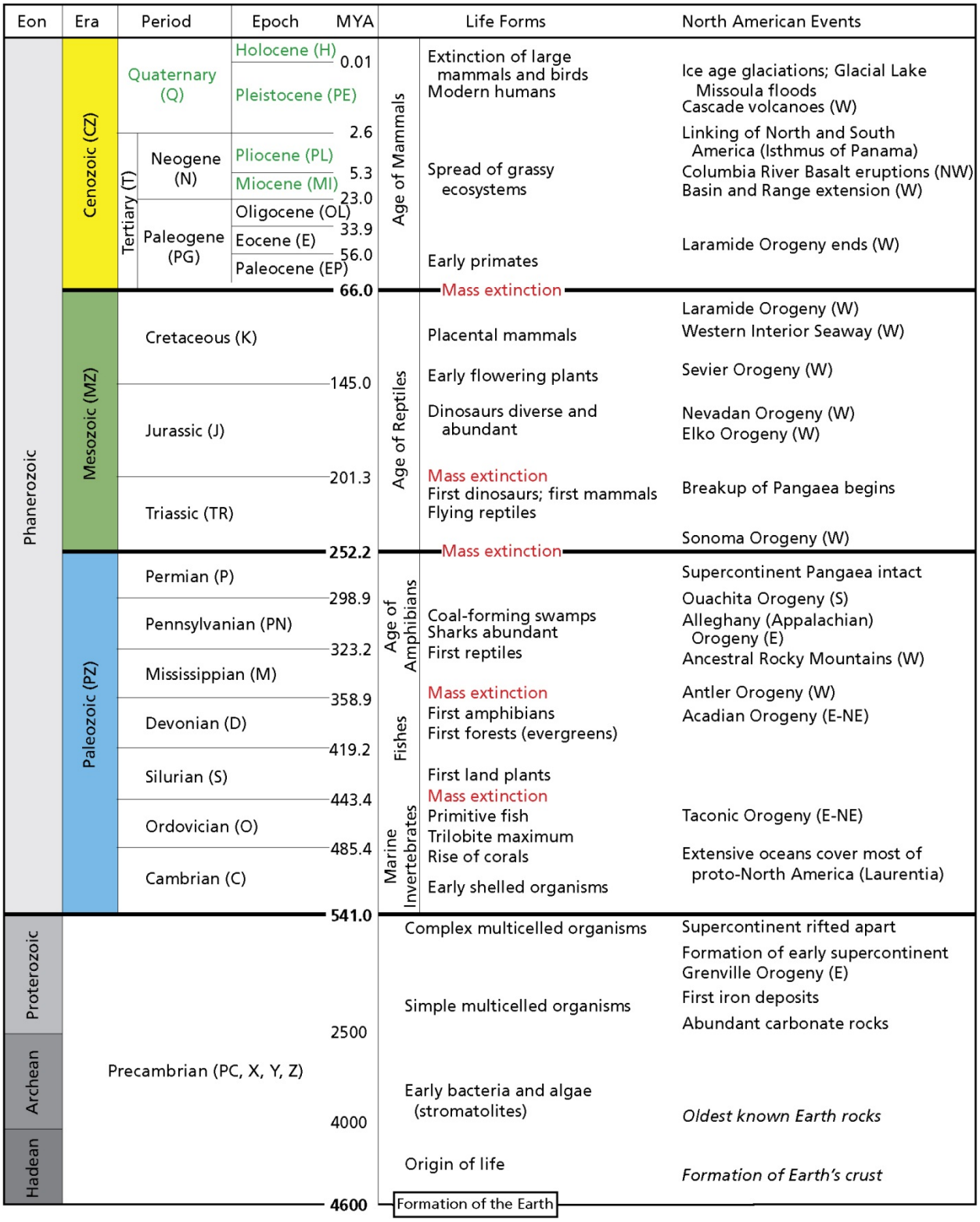

Figure 4. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. Time periods in green are represented on the GRI geologic map. GRI map abbreviations for each time division are in parentheses. Compass directions in parentheses indicate the regional locations of events. Boundary ages are millions of years ago (MYA). National Park Service graphic with dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 10 January 2014).

Era	Period		Epoch	Rock/Sediment Unit (map symbol)		Description
CENOZOIC	Quaternary		Holocene	Alluvium (Qa)		Unconsolidated deposits of clay, silt, sand, and pebbles.
			Pleistocene	Touchet Beds (Qfst2, Qfst1)		Glacial slackwater flood deposits. Rhythmically bedded layers of coarse- to fine-grained sediments. Qfst1 underlies the older, more-dissected rolling hills section of the map, and Qfst2 underlies the younger, less-dissected terraces.
				Loess (Ql2, Ql1)		Silt, clay, and fine sand. Ql1 underlies the older, more-dissected rolling hills section of the map, and Ql2 underlies the younger, less-dissected terraces.
	Tertiary	Neogene	Pliocene and Miocene	Conglomerate (PLMIcg)		Sandy gravel with clasts of predominantly well-rounded basalt. Underlies much of the Walla Walla Basin.
				Fine-grained sediments (PLMIf)		Silt, sandy silt, sandy mud, and blue, green, and yellow clay identified only in the subsurface.
			Miocene	Wanapum Basalt	Frenchman Springs Member (MIvwfs)	Basalt. The Wanapum Basalt is part of the Columbia River Basalt Group.

Figure 5. General stratigraphic column for the Whitman Mission National Historic Site area. Derkey et al. (2006) was the source map for the GRI digital data and descriptions. Colored units have been mapped within the park. Coloration follows the standard approved by the US Geological Survey to indicate time periods on geologic maps and corresponds to colors used on the Map Unit Properties Table. See the Map Unit Properties Table for more detail.

be found in the map's northwestern corner (see poster in pocket). At Whitman Mission, the basalt lies approximately 160 m (524 ft) beneath the surface.

Erosion of this basalt during the Miocene and Pliocene generated conglomerate (PLMIcg; southeastern portion of digital map) and fine-grained sediments (PLMIf). The sediments have been found only in boreholes drilled in the Columbia Basin (Derkey et al. 2006).

The fertile soils in the Walla Walla Valley that overlie Pliocene sediments and made a positive impression on the Whitmans developed from deposits of fine-grained loess (Ql2, Ql1). During the Pleistocene (fig. 4), enormous ice sheets covered much of North America and glaciers flowed as far south as the current locations of Spokane and Olympia. Some glaciers were more than 1 km (0.6 mi) thick, and ice pulverized and ground up pieces of bedrock into silt-sized particles. Meltwater from glacier fronts carried these silt particles away from the glaciers, and when the glaciers receded, prevailing winds from the southwest spread loess over the stark, barren landscape. Loess deposits in the Columbia Basin are up to 60 m (200 ft) thick. Because loess-rich soils provide ideal conditions for wheat cultivation, southeastern Washington has become one of the major grain-producing regions of the world (Lasmanis 1991).

During the Pleistocene, the Purcell Trench Lobe of the Cordilleran Ice Sheet periodically flowed south in the region of present-day northern Idaho, each time creating a tremendous ice dam that formed an enormous reservoir of water known as Glacial Lake Missoula. At its maximum, Lake Missoula contained an estimated 2,100 km^3 (500 mi^3) of water, about half the volume of Lake Michigan and four times the volume of Lake Erie (Alt 2001). The ice dams failed every few decades, each time sending a towering mass of ice, water, mud, and debris down the Clark Fork, across Spokane Valley, and through the Columbia Gorge to the sea (Waitt 1985; Allen et al. 2009).

With a discharge rate of more than 20×10^6 m^3/s (700×10^6 ft^3/s) and velocity of up to 100 km/h (60 mi/h), Lake Missoula would have drained in as little as 48 hours. 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), cutting deep canyons (the "coulees" of eastern Washington) into the underlying basalt, creating gigantic ripple marks the height of three-story buildings and 30-story-high piles of gravel, and scattering 200-ton boulders from Idaho to the Willamette Valley (Baker 1987; Allen et al. 2009). The hydraulic force and concussion of floodwaters cascading over colossal cataracts formed enormous plunge pools

(Bretz 1969). For example, Dry Falls, one of many exceptional cataracts that formed in the floods, is up to 120 m (360 ft) high and 5.5 km (3.3 mi) wide, which is about five times the width of Niagara (Baker 1987).

The magnitude of the Missoula floods suggests that these great cliffs and cataracts were submerged beneath as much as 60 m (200 ft) of the floodwaters (Allen et al. 2009). The turbulent floodwaters attacked planes of weakness in the bedrock, ripped up chunks of basalt, and gouged the bedrock to form the great Channeled Scablands of eastern Washington (Bretz 1923, 1925, 1928a, 1959, 1969). Waterfalls contributed to some, but not all, of the scoured depressions. The waterfalls eroded headward at different rates, and evidence suggests that they retreated about 24 km (15 mi) upstream, leaving behind plunge pools and small lakes, such as Fall Lake in eastern Washington (Bretz 1969; Alt 2001; Allen et al. 2009).

Torrents of murky, turbulent, sediment- and debris-laden floodwaters hit the narrow passage at Wallula Gap. Located about 40 km (25 mi) west of Whitman Mission National Historic Site, Wallula Gap forms an enormous valley where the Columbia River flows from Washington into Oregon. The gap is more than 1.6 km (1 mi) wide and 300 m (1,000 ft) deep, but could not accommodate all of the Missoula floodwaters at once. The constriction formed a hydrologic dam that created Lake Lewis (named for Meriwether Lewis of the Corps of Discovery). This temporary lake measured about 190 km (120 mi) east–west and 100 km (60 mi) north–south and flooded the Yakima and Walla Walla valleys (Allen et al. 2009).

In the quiet slackwaters of Lake Lewis, coarse-grained and then fine-grained sediments settled out of the water column. The settling process formed graded beds with coarse sediments at the bottom and finer sediments at the top, called rhythmites, which were first described near Touchet, Washington, in the Walla Walla Valley. The Touchet Beds (Qfst2, Qfst1) have been removed by river and stream erosion in some locations, but a remnant of these glacial slackwater deposits is preserved in the hill at Whitman Mission National Historic Site. Significantly, the rhythmites in the Touchet Beds demonstrated that Glacial Lake Missoula produced at least 40 outburst floods (known as jökulhlaups), rather than a single flood event (Waitt 1980, 1984; Allen et al. 2009).

Today, the Glacial Lake Missoula floods and the enormous features they produced are accepted as excellent examples of numerous catastrophic events punctuating the geologic record. The National Park Service (NPS) has proposed the development of an Ice Age Flood National Geologic Trail to help tell the extraordinary story of the floods (NPS 2001). In the 1920s, when J. Harlen Bretz first proposed that a catastrophic flood had occurred, he ignited a firestorm of controversy in the geologic community, which was opposed to so-called "catastrophism" (Alden et al. 1927; Bretz 1928b, 1930). For decades, early-20th-century geologists had moved away from catastrophism and shifted their thinking toward uniformitarianism, which is framed by "slow" geologic processes (Allen et al. 2009). Despite his exceptional documentation through field evidence, Bretz's hypothesis of a "Spokane Flood" was not accepted for decades.

In 1942, two decades after Bretz first proposed his hypothesis, Joseph Pardee, a colleague who had worked with Bretz in the field, outlined the features of Glacial Lake Missoula (Pardee 1942). He also estimated that the discharge rate from the lake must have exceeded 72 km/h (45 mi/h) to move the largest boulders displaced by the flood (Alt and Hyndman 1995). Pardee's paper gave credence to Bretz's hypothesis and descriptions of processes that resulted in the Channeled Scablands of eastern Washington (Bretz 1923, 1925, 1928a, 1928b, 1928c, 1959, 1969; Alt 2001; Allen et al. 2009).

Whereas the impressive features of the Channeled Scablands resulted from cataclysmic flood events, the rhythmites of the Touchet Beds, including those at Whitman Mission National Historic Site, record the same uniform processes that occur in modern lake environments. In effect, Bretz's catastrophic ideas have been blended with uniformitarian principles (Waitt 1985).

Since the last Lake Missoula flood occurred about 15,000 years ago, the Walla Walla River, Mill Creek, and their tributaries have distributed sediment (Qa) across the valley floor, producing the park's subdued topography and level floodplain. When the Whitmans arrived in 1836, the Walla Walla River flowed directly through the area now designated as Whitman Mission National Historic Site. A series of natural changes and agricultural practices over the past 150 years, however, have moved the Walla Walla River south of the Whitman Mission.

The restored Doan Creek currently flows through the park with carefully spaced meanders (bends), pools, vegetation, and riffles (NPS 2013a, 2013b). These features simulate natural stream conditions and provide habitat for fish and aquatic insects.

Geologic Features and Processes

This section describes noteworthy geologic features and processes at Whitman Mission National Historic Site.

Although masked by surface vegetation, the geologic features of Whitman Mission National Historic Site capture some of the dynamic processes operating in the region over approximately the past 15 million years. The geologic features and processes preserved in the historic site and surrounding area include:

- Pleistocene rhythmites from Lake Missoula floods
- Holocene alluvium
- Loess originating from Pleistocene glaciers
- Miocene Columbia River flood basalts
- Faults and folds
- Landscape features

Pleistocene Rhythmites from Lake Missoula Floods

The rhythmically bedded Touchet Beds (geologic map units Qfst2, Qfst1) provided significant evidence for the occurrence of multiple outburst floods from Glacial Lake Missoula (Bretz 1929; Waitt 1985; Alt 2001; Derkey et al. 2006; Allen et al. 2009). Spectacular water-eroded landforms, such as scoured channels, potholes, and enormous gravel bars, exist in areas where colossal floodwaters rampaged along the Columbia River and Channeled Scablands (Bretz 1928c). The number of floods that occurred in these areas is impossible to determine because each successive flood obliterated the record of previous floods. However, when catastrophic floodwaters ponded behind Wallula Gap and the current slackened in dead-end tributaries, sediment and debris settled to the bottom of Lake Lewis. Successive floods did not disturb these sediments. Rather, sediments from younger floods covered previous deposits, preserving them.

The beds form distinctive layers consisting of coarse sandy material at their bases that grades upward into finer-grained silt (fig. 6). The finer-grained sediment is abruptly overlain by coarse sediment of the next graded interval, which represents another flood event.

Two types of Touchet Bed have been mapped in the Whitman Mission region: (1) an older sequence with subtle rhythmic bedding (Qfst1) and (2) a younger sequence with conspicuous rhythmic bedding (Qfst2). Qfst1 underlies the older, more-dissected rolling hills of the north-central and northwestern parts of the map area. Qfst2 underlies the hill at Whitman Mission National Historic Site and other younger, less-dissected terraces (Derkey et al. 2006). The well-stratified younger sequence consists of fine- to medium-grained sand at the base of each interval and fine-grained silt at the top (fig. 6). Individual beds range from a few centimeters to 1 m (3 ft) thick (Waitt 1985).

Figure 6. Touchet Beds. The Touchet Beds are exposed near Lowden, Washington, approximately 11 km (7 mi) west of Whitman Mission National Historic Site. The distinct layers record approximately 40 rhythmites at this location. Photograph by user "Williamborg," used under the Creative Commons Attribution-ShareAlike 3.0 Unported License (CC by-SA 3.0). Available at http://commons.wikimedia.org/wiki/File:Touchet-formation-2.JPG (accessed 22 July 2013).

Once geologists accepted Bretz's hypothesis of a catastrophic flood, they began debating whether the colossal features were the result of one or several floods. The Touchet Beds provided critical evidence for the hypothesis that several floods occurred. Critics argued that the beds could have been the result of pulses within one huge flood, but field evidence suggested that several decades intervened between rhythmites. This evidence included channels that had eroded into some rhythmites and were subsequently infilled by sediment prior to burial by the next rhythmite, loess deposits that separated rhythmites, and a couplet of ash beds from two separate explosive eruptions of Mount St. Helens that had been deposited between two rhythmites (Waitt 1985, 1987; Busacca and McDonald 1994). Although the tops of these ash beds have been reworked by wind or sheetwash, the basal and middle portions are undisturbed, suggesting that some time elapsed between ash bed deposition events. Furthermore, the recent identification of pocket mouse and pocket gopher burrows in the Mount St. Helens ash beds and in five of seven stacked jökulhlaup deposits in Yakima Valley near Mabton, Washington, suggests that at least two or three decades (the time required for recolonization by these vertebrates) elapsed between outburst flood events (MacEachern and Roberts 2013). Spencer (1989)

discovered diverse and well-preserved rodent fauna in the Touchet Beds that showed no evidence of post-mortem transport by flooding. In contrast, the sediment in which these rodents burrowed was deposited under turbulent, flood-like conditions (Spencer 1989).

At least 40 successive, flood-laid, sand-to-silt rhythmites have been recognized in the Touchet Beds of southern Washington (Waitt 1985, 1987). The hill at Whitman Mission National Historic Site preserves part of this record.

Holocene Alluvium

The relatively flat land surrounding the hill (fig. 7) at Whitman Mission National Historic Site consists of alluvium (Qa), the unconsolidated accumulations of clay, silt, sand, and pebbles found in floodplains adjacent to stream channels. In contrast to Missoula flood deposits, the Holocene alluvium in Walla Walla Valley accumulated over thousands of years as the result of uniform, persistent processes common to streams.

Figure 7. View from the hill in Whitman Mission National Historic Site. The relatively flat topography surrounding the hill is the floodplain of the Walla Walla River and Mill Creek. National Park Service photograph by Zach Schierl.

The Walla Walla River, Mill Creek, and reconstructed Doan Creek are meandering streams; their single channels migrate back and forth across the floodplain, forming sinuous loops and curves (fig. 8). Meandering rivers erode laterally, rather than vertically, as their main currents migrate from bank to bank. Unconsolidated sediments on the outside of each meander loop are eroded, forming a "cutbank," while sediment is deposited on the inside of the meander loop, where the channel's energy decreases. These sediments form a "point bar" that progressively grows laterally in response to cutbank erosion and decreased channel velocity (fig. 8). Because these processes occur over time, characteristic features of modern streams can be used to identify past fluvial depositional environments.

The Walla Walla River and Mill Creek originate in the Blue Mountains and have the capacity to carry abundant sediment, especially during flooding. Sediment deposited during flood events may fill a river's channel, causing it to overflow its banks and carve a new channel through its floodplain. A flood that cuts through the thin neck of a meander forms an isolated C-shaped curve, called an "oxbow" or "oxbow lake" after part of a yoke for oxen (fig. 8). The Whitman's first house was constructed adjacent to a meander of the Walla Walla River, but this meander was eventually cut off and an oxbow lake formed (fig. 8). The oxbow is now dry, but a "meander scar" of this former channel consists of a shallow depression containing vegetation distinct from that of the surrounding floodplain.

Loess Originating from Pleistocene Glaciers

Although Marcus Whitman may not have appreciated the profound geologic history recorded in the land over which his wagon wheels rolled, Pleistocene glaciers and Glacial Lake Missoula floods laid the foundation for his mission and contributed to the fertile soils he found in Walla Walla Valley. Whitman considered the soil to be exceptional and superior to any soil with which he was acquainted (Schierl 2010a).

In the arid Pleistocene climates of interglacial periods, dust storms spread loess throughout the Pacific Northwest (Allen et al. 2009). Composed of tan to light-brown, massive to poorly stratified silt, clay, and fine sand, the loess (Ql1, Ql2) is about 1 m (3 ft) thick on the hill at Whitman Mission National Historic Site and ranges from about 1.5 to 15 m (5–50 ft) thick in the map area (Derkey et al. 2006). Loess deposits in other parts of the Columbia Basin are up to 60 m (200 ft) thick (Lasmanis 1991; Allen et al. 2009).

Pleistocene glaciers pulverized bedrock and sediment into fine-grained silt called "rock flour," which was carried away from the glacier margin by meltwater. Prevailing southwesterly winds then picked up the silt and deposited it as loess in the Walla Walla Valley (Robert Carson, Whitman College, Phillips Professor of Geology and Environmental Studies, written communication, 23 January 2014).

Miocene Columbia River Flood Basalts

Three small basalt exposures have been mapped in the northwestern corner of the map area (Derkey et al. 2006). Basalt is an extrusive, volcanic rock that is dark in color because it contains abundant iron-bearing minerals. The basalts in the map area are part of the Frenchman Springs Member of the Wanapum Basalt (MIvwfs), part of the Columbia River Basalt Group (table 1). The Frenchman Springs Member contains the most basalt among Wanapum Basalt members. Frenchman Springs basalt flows covered an estimated 72,595-km^2 (28,029-mi^2) area with approximately 7,628 km^3 (1,830 mi^3) of basalt (Martin et al. 2013).

When the Pleistocene Glacial Lake Missoula floods incised the Channeled Scablands into the Columbia River Basalt, ripped up pieces of basalt became part of the flood's sediment load. The turbulent floodwaters tumbled these jagged pieces of basalt until they became rounded boulders. Early inhabitants of the Walla Walla Valley carved petroglyphs into the smooth, dark surfaces of these basalt boulders.

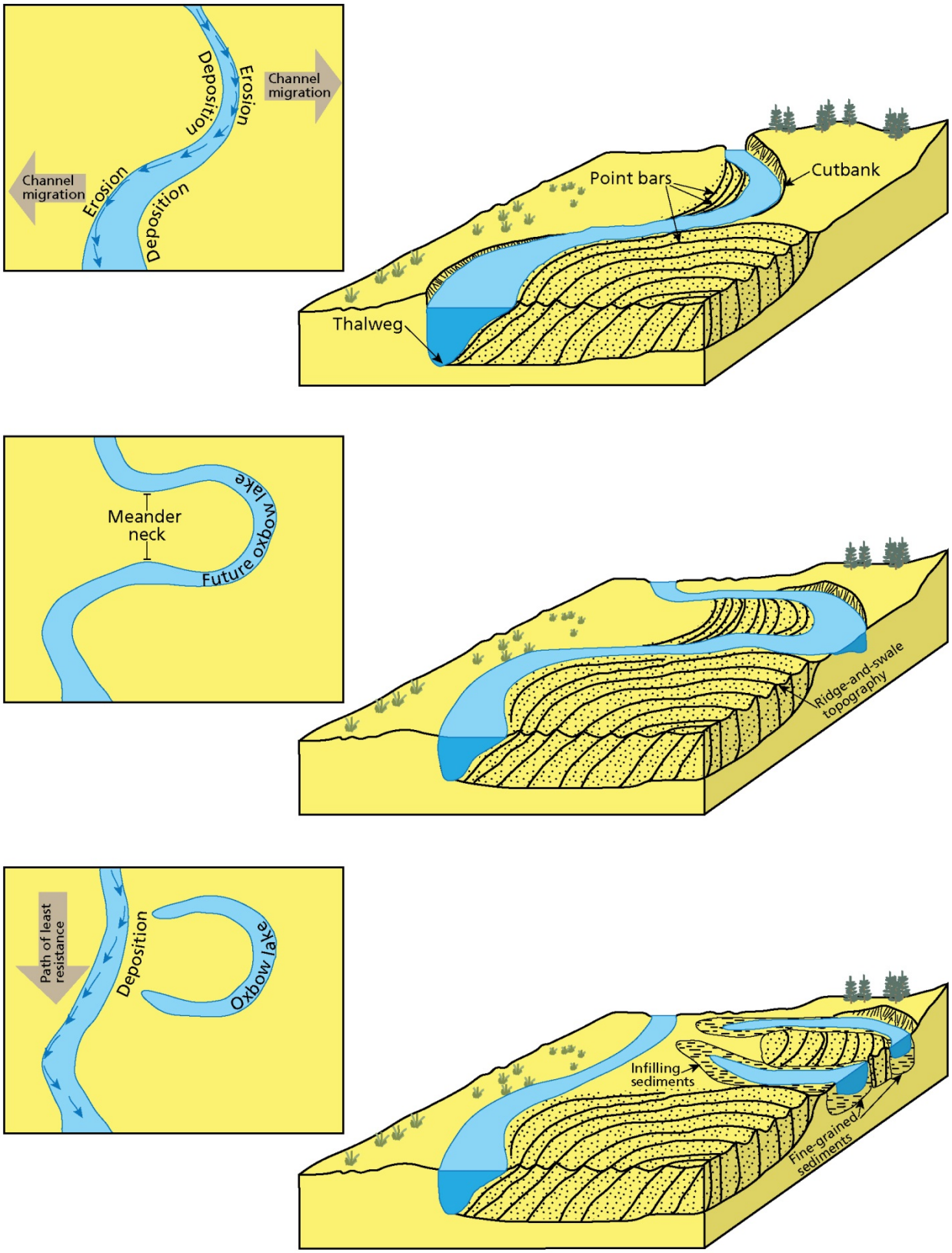

Figure 8. Schematic illustrations of features associated with a meandering stream. Point bars are areas of deposition. Lateral erosion takes place at cutbanks. The thalweg is the path of greatest current velocity, represented by arrows within the stream. When a meander neck is cut off, an oxbow lake forms. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Table 1. Stratigraphic subdivision of the Columbia River Basalt Group.

Epoch	Group	Formation (age, mya)	Member (age, mya)
Miocene	Columbia River Basalt Group	Saddle Mountain Basalt (~15–6.0)	12 members
		Wanapum Basalt (~15.6–15.0)	Priest Rapids (15.07–14.80)
			Roza (14.98–12.87)
			Frenchman Springs (16.42–12.48)
			Eckler Mountain
		Grand Ronde Basalt (~16.0–15.6) (Picture Gorge Basalt)	25 units
		Imnaha Basalt (~16.7–16.0)	
		Steens Basalt (~16.9–16.6)	

Stratigraphic sequence is from Reidel and Tolan (2013a, 2013b) and Barry et al. (2013). Ages are from Barry et al. (2013). **mya: millions of years ago.**

Faults and Folds

Several faults and folds have been mapped in Walla Walla Valley, but no fault transects Whitman Mission National Historic Site (Derkey et al. 2006). Faults in this region of southern Washington have a combination of strike-slip and normal movements (fig. 9). Northwest-striking, right-lateral and northeast-striking, left-lateral strike-slip faults have been identified in the Yakima Fold Belt, west of Whitman Mission, indicating that the principal compressive stress is oriented north-northwest (Anderson et al. 2013). Near Whitman Mission National Historic Site, normal faults have offset Miocene and Pliocene stratigraphic units (see cross-section on poster in pocket). The College Place Fault acts as a groundwater barrier in the Walla Walla area. Offset along this fault ranges from 30 to 60 m (100–200 ft) (Derkey et al. 2006).

The two faults nearest the park are the northeast–southwest-trending College Place Fault to the north and the west-northwest–east-southeast trending Mud Creek Fault to the south. The faults offset Miocene–Pliocene fine-grained sediments (PLMIf), but do not continue into Miocene–Pliocene conglomerate (PLMIcg; see cross-section on map poster [in pocket]). Offset on the Mud Creek Fault is more than 60 m (200 ft) (Derkey et al. 2006). The Pedigo Fault cuts the Miocene–Pliocene conglomerate (PLMIcg) and thus is younger than the College Place and Mud Creek faults, which cut only the older Miocene–Pliocene fine-grained sediments (PLMIf).

The west–east-trending axis of the Walla Walla syncline (concave fold) lies approximately 1 km (0.6 mi) south of the park. The broad syncline has been identified by depth-to-basalt data from water wells. This feature, however, may be the result of faulting rather than folding, in which case it would be a graben (Derkey et al. 2006).

Landscape Features

Three geomorphic units have been mapped in the vicinity of Whitman Mission National Historic Site: terraces, rolling hills, and modern valleys (Derkey et al. 2006). Terraces, including the hilltop at Whitman Mission, are found in three areas: (1) the gently west-sloping area immediately north of Mill Creek Valley, (2) east and southeast of Walla Walla, Washington, and (3) in isolated hills surrounded by stream valleys west and southwest of Walla Walla. The rolling hills geomorphic unit is north of US Highway 12 (Derkey et al. 2006). The active floodplains of the Walla Walla River and its tributaries form the modern valleys, the third geomorphic unit.

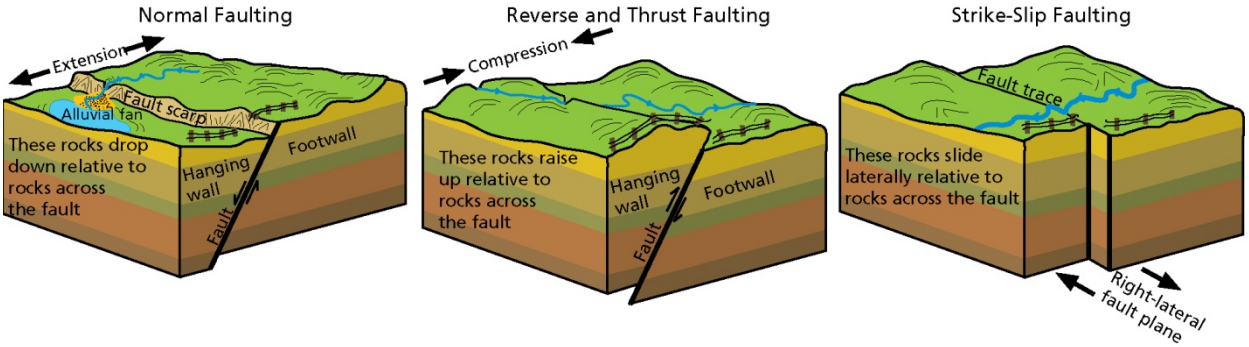

Figure 9. Schematic illustrations of fault types. Footwalls are below the fault plane and hanging walls are above it. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging wall up relative to the footwall. A thrust fault is similar to a reverse fault, but has a dip angle of less than 45 degrees. 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 combination of strike-slip and normal faulting occurs in Walla Walla Valley. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Geologic Resource Management Issues

This section describes geologic features, processes, or human activities that may require management for visitor safety, protection of infrastructure, and preservation of natural and cultural resources at Whitman Mission National Historic Site. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

The following geologic issues are of potential concern to resource managers at Whitman Mission National Historic Site:

- Flooding
- Seismic activity (earthquakes)
- Doan Creek restoration
- Geothermal energy development

Flooding

The Whitmans built their first house in 1836 near the confluence of the Walla Walla River and Mill Creek (fig. 1). Although this location provided easy access to water, it was also susceptible to flooding. They moved their house in 1838 to higher ground, but still within the floodplain of the Walla Walla River and Mill Creek. Immigrants who followed the Whitmans also built on the floodplain. In 1859, Walla Walla became a city, and increased construction and infrastructure development increased the risk of significant flood damage.

Mill Creek, which flows through the northwestern corner of Whitman Mission National Historic Site, is prone to flooding. The creek originates in the Blue Mountains, east of the park, and flows through a narrow, steep-sided canyon cut into the Columbia River Basalt Group before entering the Walla Walla Valley. Mill Creek slopes steeply in the canyon, dropping about 14 m/km (72 ft/mi) compared with 8 m/km (40 ft/mi) in the valley (US Army Corp of Engineers 1972, 1999; Walla Walla Regional Planning Department 1999). The steepness of the slope and narrowness of the canyon produce deep, high-velocity floods. When flooding, Mill Creek contains a high sediment load consisting of clay, silt, sand, pebbles, cobbles, and boulders.

The US Army Corps of Engineers began the Mill Creek Project after the especially devastating flood of 1931 and completed it in 1942 (fig. 10). The project comprised construction of the 38-m- (125-ft-) high, 1,000-m- (3,300-ft-) long Mill Creek Dam, the Bennington Reservoir behind the dam, and the 10-km- (6-mi-) long Mill Creek Channel through the city of Walla Walla (US Army Corps of Engineers 2013). These structures resulted in the successful diversion of major floods in 1964 and 1996, but the channel's ability to contain future floods is not guaranteed. The Mill Creek Project has potentially protected Walla Walla and Whitman Mission National Historic Site from flooding, but it also reduced the natural habitat for fish and other organisms. To allow passage and provide resting places for migrating fish, two fish ladders were installed and large boulders were placed in the Mill Creek Channel. Fish screens were also installed in Bennington Lake to prevent the trapping of fish (US Army Corps of Engineers 2013). As of January 2014, the weirs that direct fish to the fish ladders were being notched (Robert Carson, Whitman College,

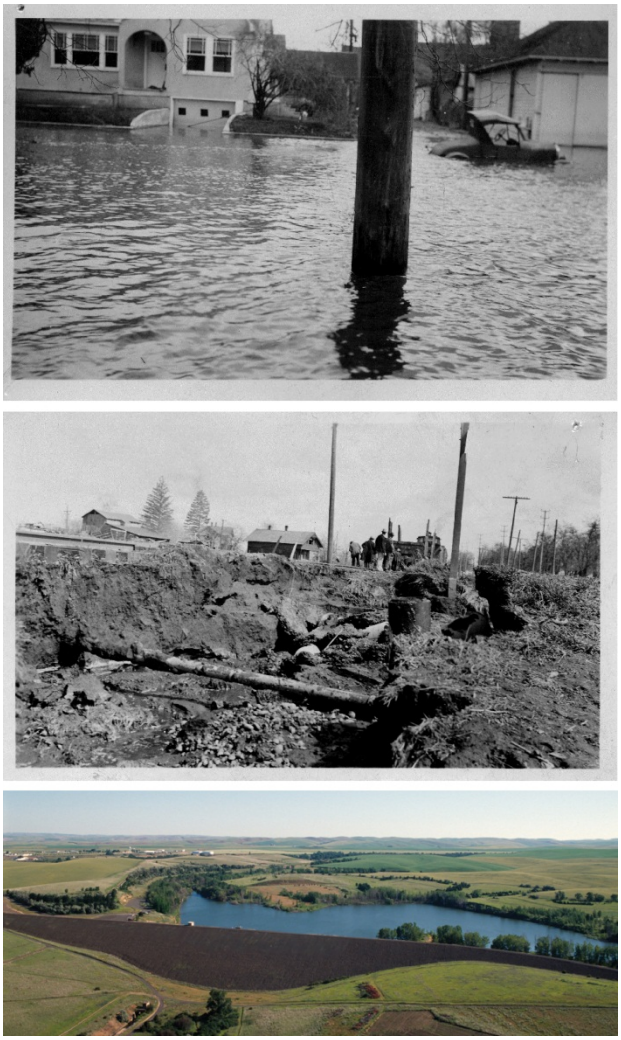

Figure 10. 1931 flood damage. The 1931 flood that inundated Walla Walla, Washington (upper and middle photographs) triggered construction of the Mill Creek Dam on Russell Creek, which created the Bennington Reservoir (bottom photograph). Flood photographs taken by the City of Walla Walla, Flood Control Commission, available from the Washington State Archives, Digital Archives, available at: http://www.digitalarchives.wa.gov/Collections/TitleInfo/1681 (accessed 29 July 2014). Bennington Reservoir photograph by the US Army Corps of Engineers, available at: http://www.nww.usace.army.mil/Locations/DistrictLocksandDams/MillCreekDamandBenningtonLake.aspx (accessed 29 July 2014).

Phillips Professor of Geology and Environmental Studies, written communication, 23 January 2014).

Flood potential in the Walla Walla Valley may increase due to the combined effects of seasonal variations in precipitation and Chinook weather conditions, characterized by warm temperatures and winds. Chinook conditions rapidly melt snow and may trigger flooding. Flood potential increases further when snow melt occurs on frozen ground, which increases runoff. Heavy precipitation compounds the problem. These factors combined to produce major flooding on Mill Creek in March 1931, December 1964, and February 1996.

Global climate change may affect the intensity, duration, and frequency of precipitation and subsequent flooding in the Walla Walla Valley . The Cascade Mountains block the passage of rain-producing weather systems from the Pacific, dividing Washington into two distinct climatic regimes, with the eastern region receiving considerably less precipitation. For example, the Olympic Mountains receive more than 5 m (16 ft) precipitation annually, whereas the high Columbia Plateau in eastern Washington may receive less than 20 cm (8 in) (Snover et al. 2013). About 75% of precipitation in Washington falls during the cool season (October–March), and the snowpack sustains warm-season streamflows.

Small changes in temperature can significantly alter the balance of precipitation falling as rain and snow, thereby affecting the timing of streamflow. For the Pacific Northwest, models of global climate change predict a temperature increase of 1.7°C to 6°C (3–10°F) over this century, as well as increased winter and decreased summer precipitation (Karl et al. 2009; Mote et al. 2013; Raymondi et al. 2013). Changes in the timing of snowmelt will cause impact water supply throughout the northwest leading to major ecological and sociological consequences (Mote et al. 2014). In areas receiving snow, such as the Blue Mountains, streamflow is projected to increase in winter and early spring and decrease in late spring, summer, and fall. Combined with Chinook weather conditions, these changes may produce more intense flood events in the Walla Walla Valley.

Although the impacts of global climate change are projected to be more dramatic along the coast and west of the Cascade Range, regional simulations also show an increase in precipitation for eastern Washington. Changes in circulation patterns will reduce the rainshadow effect of the Cascades, allowing more moisture to reach eastern Washington (Salathé et al. 2009).

Seismic Activity (Earthquakes)

Earthquakes in Washington occur primarily in the western part of the state. The last earthquake to impact the Walla Walla region occurred on 15 July 1936, when a magnitude 5.75 earthquake centered near the Washington state line cracked walls, chimneys, and concrete pavement in State Line, Freewater, and Umapine, Oregon, and collapsed chimneys in Waitsburg, Washington (US Geological Survey 2012). Since 2000, seven earthquakes with magnitudes of 1.6 to 3.4 have occurred within 34 km (21 mi) of Walla Walla (http://earthquaketrack.com/us-wa-walla/recent, accessed 27 August 2013). The US Geological Survey maintains an online application to estimate the probability of a particular magnitude earthquake occurring over a specified time period. The tool is available at: http://geohazards.usgs.gov/eqprob/2009/index.php (accessed 29 July 2014). According to that tool, there is between a 0.15 and 0.20 probability (between 15% and 20%) of a magnitude 5.5 earthquake occurring near Walla Walla, Washington during the next 100 years (fig. 11).

Microearthquake swarms with magnitudes of less than 3 have occurred in the Saddle Mountains and Frenchman Hills, approximately 120 km (75 mi) northwest of Whitman Mission National Historic Site, and in Horse Heaven Hills, approximately 50 km (30 mi) west of the park (Rohay 2006).

Quaternary faults have been identified in south-central Washington, and faulting has continued since the last cataclysmic flood occurred about 13,000 years before present (Anderson et al. 2013). Reverse and strike-slip movements have occurred on Pleistocene faults in the Walla Walla Valley, but no recent (Holocene) movement on these faults has been documented (Reidel et al. 1994). Some faults in the region are associated with the northwest–southeast-trending Olympic Wallowa Lineament, which transects Washington from the Olympic Peninsula to the Blue Mountains, and current north–south compression of Washington State (Reidel et al. 1994). Strike-slip faulting in the Yakima Fold Belt west of Whitman Mission National Historic Site has continued since the emplacement of the Columbia River basalt (Anderson et al. 2013). Because tectonic compression continues to affect the Columbia Basin, earthquakes remain a potential hazard for Walla Walla Valley.

Doan Creek Restoration

Immigrants straightened the channel of Doan Creek to create an irrigation ditch. Dams and irrigation projects decreased fish and riparian habitat throughout Walla Walla Valley. Salmon and steelhead populations in the relatively dry Walla Walla Valley have declined dramatically since the time of the Whitmans.

Washington State law requires the installation of fish screens between irrigation water and streams that could contain fish. Facing a citation due to the lack of a fish screen, park staff seized the opportunity to restore Doan Creek's original water course, which had not been used for more than 70 years (NPS no date given).

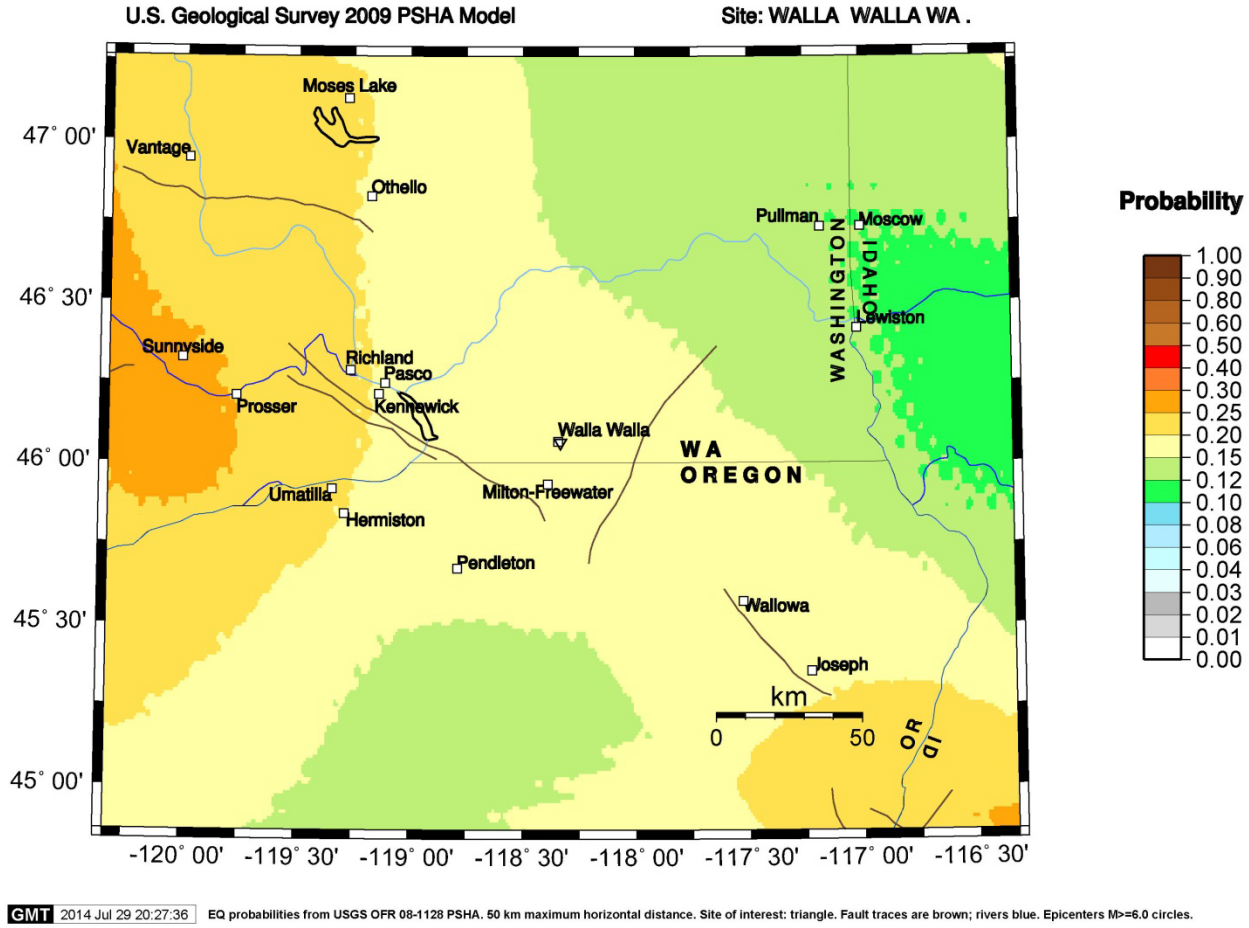

Figure 11. Probability of magnitude 5.5 or greater earthquake within 100 years at Walla Walla, Washington (center of map). Map created by the US Geological Survey 2009 Earthquake Probability Mapping tool, available at: http://geohazards.usgs.gov/eqprob/2009/index.php (accessed 29 July 2014).

Figure 12. Old and new channels of Doan Creek. The old channel followed the path of the irrigation ditch (2003 image). The restored Doan Creek (2013 image) contains meanders, pools, riffles, and riparian vegetation that provide habitat for fish, aquatic insects, and other animal and plant life. 2003 imagery from the National Agricultural Imagery Program (NAIP), available at http://datagateway.nrcs.usda.gov/ (accessed 13 August 2014). 2013 imagery from ESRI World Imagery Basemap layer (accessed 13 August 2014; sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community).

The environmental assessment for the Doan Creek Restoration Project listed the following three objectives (NPS no date given):

- To restore natural processes to Whitman Mission National Historical Site
- To increase the potential for wildlife in the northern fields of the park, where the original channel was located
- To reintroduce fish passage from Mill Creek to Doan Creek

As the project developed, upstream water users also became involved. Park managers; private landowners; representatives of other government agencies, Whitman College, and Walla Walla University; and volunteer groups worked together to create adequate habitat for wildlife while providing sufficient water for other uses (NPS 2013b).

Following planning and funding approval, park staff began to restore the original Doan Creek channel in 2005. Today, the restored creek contains features such as meander bends, pools, and riffles that simulate natural stream conditions, and provides ideal habitat for fish, especially the threatened/endangered steelhead and salmon (fig. 12; NPS 2013a).

Geothermal Energy Development

Washington is divided into two primary geothermal resource areas: (1) a high-temperature area located primarily in the Cascade Range and (2) a low-temperature area in the Columbia Basin (Korosec et al. 1981; Washington Department of Natural Resources 2013). The Walla Walla Valley is located in a low-temperature resource area characterized by thermal waters with temperatures of at least 20°C (68°F). In contrast, geothermal systems in the Cascades contain thermal waters with approximate temperatures of at least 100°C (212°F).

Most bottom-hole temperatures in thermal wells drilled in Walla Walla County range from 20°C to 30°C (68–86°F) (Korosec et al. 1981). Heat-flow gradients range from 27°C to 92°C/km (130–320°F/mi). Wells are relatively shallow (typically 200–300 m [660–1,000 ft] deep), which encourages development of geothermal energy (Korosec et al. 1981).

The impact of geothermal development in Walla Walla Valley on Whitman Mission National Historic Site has not been evaluated. Geothermal energy could be used to heat the park's visitor center and other buildings.

Geologic History

This section describes the chronology of geologic events that formed the present landscape of Whitman Mission National Historic Site.

The geologic history of Whitman Mission National Historic Site and the Walla Walla Valley involves two extreme catastrophic events. In the Miocene, basalt flows inundated the Columbia Basin, including all of southeastern Washington. In the Pleistocene, massive floods left features on the landscape that today are visible from space. The rocks in and around the park record events that occurred within the past approximately 15 million years of Earth history, from the Miocene to the present (figs. 4 and 5).

In Washington, the Columbia Basin, bordered by the Cascade Range and Rocky Mountains, can be subdivided into three subprovinces: (1) the Yakima Fold Belt, (2) the Palouse Slope, and (3) the Blue Mountains (fig. 13). Whitman Mission National Historic Site is located near the border of the Yakima Fold Belt and the Blue Mountains. The Yakima Fold Belt contains the most deformation, with a series of folds that are oriented predominantly east–west. The Palouse Slope shows little deformation. Except for a few faults and low-amplitude, long-wavelength folds, this subprovince consists of a gently westward-dipping bedrock slope buried by overlying sediment (Swanson et al. 1980; Reidel et al. 1994). The Blue Mountains form the southeastern border of the Walla Walla Valley.

The Columbia Basin contains the boundary between the stable North American craton to the east and accreted land masses to the west and south. The Yakima Fold Belt overlies a basin that formed prior to Columbia River Basalt Group (CRBG) deposition and was filled with as much as 7,000 m (23,000 ft) of continental sediments (Reidel et al. 1994). In contrast, a thin (<100 m [300 ft]) discontinuous sediment package separates the basalt from the slightly metamorphosed sedimentary (metasedimentary) and igneous basement rocks underlying the Palouse Slope. These metasedimentary rocks are exposed along the northeastern and eastern margins of the Columbia Basin (Reidel et al. 1994).

Jurassic and Cretaceous granitic rocks extend from Idaho into northeastern Washington, and Cretaceous plutons, consisting primarily of granite, are exposed in steptoes in southeastern Washington. Steptoes are topographic features that project like islands above the lava field of Miocene basalts along the Idaho border south of Spokane (Lasmanis 1991). They are the remnants of mountain summits and were named for Steptoe Butte, which protrudes above the Columbia Plateau lava flows near Colfax, Washington, approximately 150 km (95 mi) northeast of Whitman Mission National Historic Site. Pre-basalt granitic rocks are also exposed in steptoes near Johnson, Washington, and Granite Point on the Snake River, south of Pullman (Hooper and Rosenberg 1970; Wright 1999).

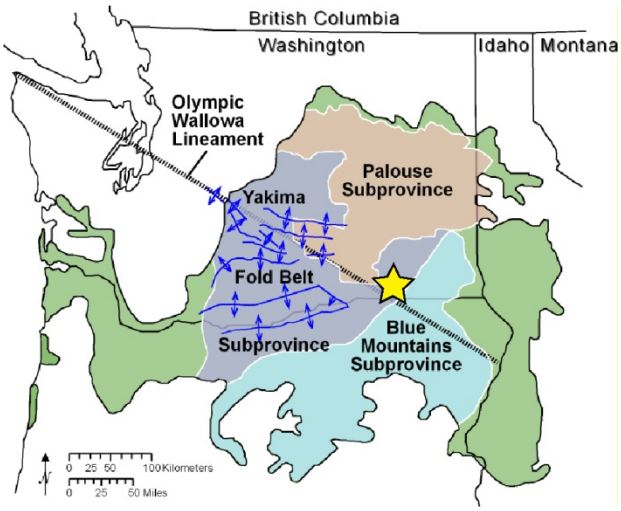

Figure 13. Schematic map showing the subprovinces of the Columbia Basin and Olympic Wallowa Lineament. The yellow star marks the approximate location of Whitman Mission National Historic Site. Simplified from Reidel et al. (2003, fig. 1) and available at http://geology.isu.edu/Digital_Geology_Idaho/Module10/mod10.htm (accessed 29 July 2014).

The Columbia Basin before Basalt Deposition: Pre-Miocene

The only rocks in the Columbia Basin older than the CRBG are exposed around the basin's margin, and their ages and lithological characteristics vary considerably. A small amount of data about these rocks has been collected from hydrocarbon exploration boreholes, seismic refraction surveys, and gravity studies (Reidel et al. 1994). On the western edge of the Columbia Basin, younger volcanic rocks erupted from the Cascade Range have obscured this earlier history, although local erosion has exposed some older rocks.

The metamorphosed rocks of the Palouse Slope resemble rocks of the Precambrian Belt Supergroup, exposed in Washington, Idaho, Montana, and British Columbia, and prominent in Glacier National Park (see GRI report by Thornberry-Ehrlich 2004). They are part of the old, stable continental craton (Reidel et al. 1994).

The sediments filling the pre-CRBG basin in the Yakima Fold Belt are much younger than the Precambrian bedrock beneath the Palouse Slope. They consist of Paleocene, Eocene, and Oligocene continental and volcanic-derived sediments (Reidel et al. 1994).

In the southern part of the Columbia Basin, Paleogene (middle Tertiary) volcanic rocks and associated volcaniclastic rocks of the Clarno and John Day formations underlie the CRBG (Reidel et al. 1994). These units are exposed at the surface in John Day Fossil Beds

Figure 14. Distribution of the Columbia River Basalt Group and the Wanapum Basalt. The yellow star marks the approximate location of Whitman Mission National Historic Site. Graphic by Trista Thornberry-Ehrlich 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 (National Park Service), available at http://www.shadedrelief.com/physical/index.html (accessed 30 July 2013).

National Monument in eastern Oregon (see GRI report by Graham in prep.).

During the Mesozoic, subduction along the western margin of North America accreted several landmasses to the North American continent. Paleozoic and Mesozoic rocks of various regionally extensive landmasses form the foundation of the 140,000-km^2 (55,000-mi^2) landscape of the Blue Mountains, southeast of Walla Walla Valley and Whitman Mission National Historic Site (Orr and Orr 2012). The boundary between the Blue Mountains and the pre-CRBG basin is not precisely located, but it may coincide with a feature called the Columbia Transarc Lowland (Beeson et al. 1989; Reidel et al. 1994). This linear, northeast-trending trough through the Columbia Basin contains the thickest pre-CRBG sediment package and the most CRBG flows in the basin. It was the main conduit for CRBG flows between the vent area and Washington (Reidel and Tolan 1992).

Massive Flows of Basalt: The Miocene

The CRBG represents one of the largest basaltic lava floods ever to occur on Earth (fig. 14). With an eruption temperature of approximately 950°C (1,700°F), the Columbia River basalt was relatively fluid, similar to basaltic lava from the vents in Hawai‘i Volcanoes National Park (see GRI report by Thornberry-Ehrlich 2009). Between 17.5 million and 6 million years ago, 174,000 km^3 (41,700 mi^3) of basaltic lava that now covers 164,000 km^2 (63,000 mi^2) of eastern Washington and Oregon and western Idaho flooded the Columbia Basin

(fig. 14; Swanson et al. 1989; Reidel et al. 1994; Barry et al. 2013; Reidel and Tolan 2013a, Reidel et al. 2013). More than 300 individual high-volume (up to 5,000 km^3 [1,200 mi^3]) lava flows and countless small flows are represented in the CRBG. Basalt thickness ranges from 500 to 1,500 m (1,600–4,900 ft) on the Palouse Slope and is dramatically greater (up to 4,000 m [13,000 ft]) in the Yakima Fold Belt (Reidel et al. 1994).

Approximately 10,800 km^3 (2,590 mi^3) of Wanapum Basalt poured onto the Columbia Plateau between 15.8 million and 14.8 million years ago (fig. 14) (Baski 2013). This massive amount, however, represents only about 6% of the total flood basalts. The Grande Ronde Basalt, 151,700 km^3 (36,390 mi^3) of which erupted from approximately 16 million to 15.6 million years ago, makes up approximately 87% of the CRBG (table 1; Barry et al. 2013).

Research continues regarding the origin of the Columbia River basalts (Barry et al. 2013). A mantle plume hypothesis suggests that basalt outpouring was caused by the deep mantle upwelling that gave rise to the Yellowstone hot spot. As the North American continent drifted westward, the mantle hot spot tracked northeastward across the Snake River Plain. Evidence for the mantle plume head today consists of a broad swelling in the lithosphere, high heat flow in Idaho's subsurface, and seismic waves that travel slowly in the subsurface, suggesting greater-than-normal heat (Camp and Ross 2004; Camp 2013).

A recently proposed hypothesis for the origin of these flood basalts involves a "slab tear" event that began in the region of present-day eastern Oregon approximately 17 million years ago (Liu and Stegman 2012). According to this hypothesis, a piece of the Farallon Plate broke off as it was subducted beneath the North American Plate, creating a 900-km- (600-mi-) long rupture in the region of present-day eastern Oregon and northern Nevada. Flood basalts erupted from this slab tear and spread across the Columbia Basin (Camp and Ross 2004; Liu and Stegman 2012). These flood basalt eruptions terminated in the region of present-day Oregon and Washington approximately 6 million years ago, but continued east through the Snake River Plain (Liu and Stegman 2012; Robert Carson, Whitman College, Phillips Professor of Geology and Environmental Studies, written communication, 23 January 2014).

Folding and faulting occurred in the Yakima Fold Belt as the Columbia River basalts erupted (Anderson et al. 2013). North–south-directed compression formed east–west-trending narrow ridges (anticlines) separated by broad valleys (synclines). Reverse faults cut the folds. The fold belt controlled the thickness of subsequent basalt eruptions, with the thickest flows forming in synclines (Reidel et al. 2003).

A northwest–southeast-trending major topographic feature, called the Olympic-Wallowa Lineament (fig. 13), transects the Columbia Basin and crosses from Washington into Oregon at Wallula Gap, west of Whitman Mission National Historic Site. The lineament's significance and association with any known structure are controversial, but evidence from the Blue Mountains suggests that right-lateral strike-slip movement occurred on the lineament before, during, and after the eruption of the Columbia River basalts (Reidel et al. 1994; Kuehn 1995, 1996).

The massive outpouring of the CRBG transformed the Columbia Basin into a shallow, bowl-shaped, nearly featureless plain. By 6 million years ago, eruptions had buried most anticlines and other topographic features. A few anticlinal ridges in the Yakima Fold Belt were not entirely inundated by younger flows. The ancestral Columbia River and its tributaries flowed across this barren landscape (Reidel et al. 1994).

Sedimentation following the emplacement of the Columbia River basalt flows, during the rest of the Miocene and Pliocene, was confined primarily to synclines. Yakima folds continued to grow, displacing gravel-rich, south-flowing river channels. As channels shifted across the basin, gravel deposits were overlain by overbank sand and silt (geologic map units PLMIcg and PLMIf). About 5 million years ago, widespread lacustrine (lake) systems grew throughout the basin. Then, about 3.5 million years ago, lake conditions ended with the region-wide incision of the Columbia River system. Several factors (or a combination thereof), including uplift rates, changes in detrital input from northern sources, increased Cascadian volcanism in the Columbia River Gorge, and headward erosion, may have contributed to a change in base level and subsequent incision of the Columbia River (Tolan and Beeson 1984; Tolan et al. 1984; Reidel et al. 1994). An unconformity marks the contact between the uppermost Pliocene sediments and initial Pleistocene deposits (Reidel et al. 1994).

Catastrophic Floods and the Rhythmites of Whitman Mission: The Pleistocene

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. 15; Booth et al. 2004). At times, the Cordilleran Ice Sheet coalesced with the western margin of the larger Laurentide Ice Sheet to cover a continuous area of more than 4,000 km (2,500 mi) 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 an ice dam with a height of up to 760 m (2,500 ft) and width of more than 48 km (30 mi). At its maximum, probably about 18,000 calendar years (15,000 radiocarbon years) before present, the dam contained up to 210 km^3 (50 mi^3) of ice (Booth et al. 2004; Allen et al. 2009).

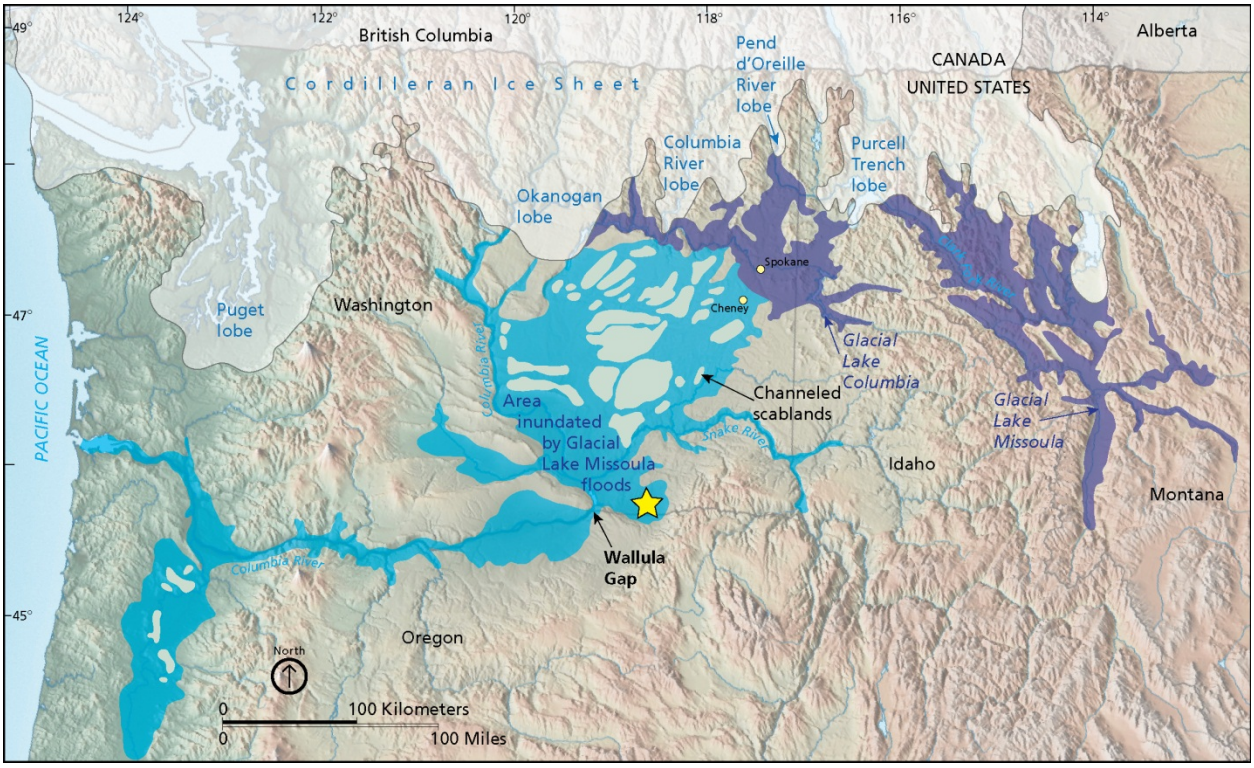

Figure 15. Map of Cordilleran Ice Sheet and glacial lakes. The Purcell Trench lobe advanced southward and formed an ice dam that blocked the Clark Fork River, forming Glacial Lake Missoula. The area affected by the Missoula floods is shown in light blue. Lake Lewis formed behind Wallula Gap and encompassed the present-day location of Whitman Mission National Historic Site (yellow star). Graphic by Trista Thornberry-Ehrlich (Colorado State University), with information from a US Geological Survey diagram, available at http://pubs.usgs.gov/sir/2005/5227/section5.html (accessed 30 July 2013). Base map by Tom Patterson (National Park Service), available at http://www.shadedrelief.com/physical/index.html (accessed 30 July 2013).

Behind the ice dam, Lake Missoula grew to cover approximately 7,500 km^2 (2,900 mi^2). When filled to its maximum, Lake Missoula 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). How the dam failed remains a matter of conjecture. Water may have overtopped it, causing it to break. Subglacial tunneling in the ice, which is common in glaciers, may have caused the dam to fail. Lake water may have lifted or floated the ice dam, allowing water to escape beneath it as the ice disintegrated (Allen et al. 2009). 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 (Roberts et al. 2002; Clague et al. 2003).

When the ice dam burst by whatever means, an estimated 2,100 km^3 (500 mi^3) of water and 210 km^3 (50 mi^3) of ice and debris rampaged west-southwest across the region of present-day Idaho and carved the anastomosing pattern of channels and gravel bars, steep canyons and isolated buttes, potholes and plunge pools of the Channeled Scablands of eastern Washington (Bretz 1969). These jökulhlaups created features found in normal river systems, but of immense proportions (fig. 16). For example, the Missoula floods produced ripple marks, which commonly form in streams, such as those produced in the fine sediment of Doan Creek. These ripples, however, were not of the typical centimeter scale; they formed 6- to 9-m- (20–30-ft-) high, kilometer-long gravel ridges separated by 60 to 90 m (200–300 ft) (Allen et al. 2009). Colossal gravel bars hundreds of meters high were deposited in channels carved by the floods (Bretz 1928c). In the Portland Basin, boulders in Missoula flood gravel bars exceed 5 m (16 ft) in diameter. Fort Vancouver National Historic Site is located on a terrace formed in Missoula Flood gravel deposits (Graham 2009).

Slowed by Wallula Gap (fig. 17), the floodwaters backed up to form Lake Lewis (fig. 18). Sediment settled out of the water column to form the rhythmites in the Touchet Beds (Qfst2, Qfst1), some of which are preserved in the hill at Whitman Mission National Historic Site. At least 40 cataclysmic floods of tremendous force and dimensions surged across the Columbia River drainage basin and filled Lake Lewis at the end of the last glaciation, between 15,000 and 18,000 calendar years before present (fig. 18; Waitt 1980, 1984; Allen et al. 2009).

The cataclysmic floods scoured the Channeled Scablands, eroding unconsolidated sediment and pieces of bedrock (Bretz 1923, 1925, 1928a, 1959, 1969). Loess, which had previously been spread throughout the region of present-day south-central Washington, became part of the sediment load in the turbulent floodwaters. In the backwaters of Lake Lewis, silt settled out of the water

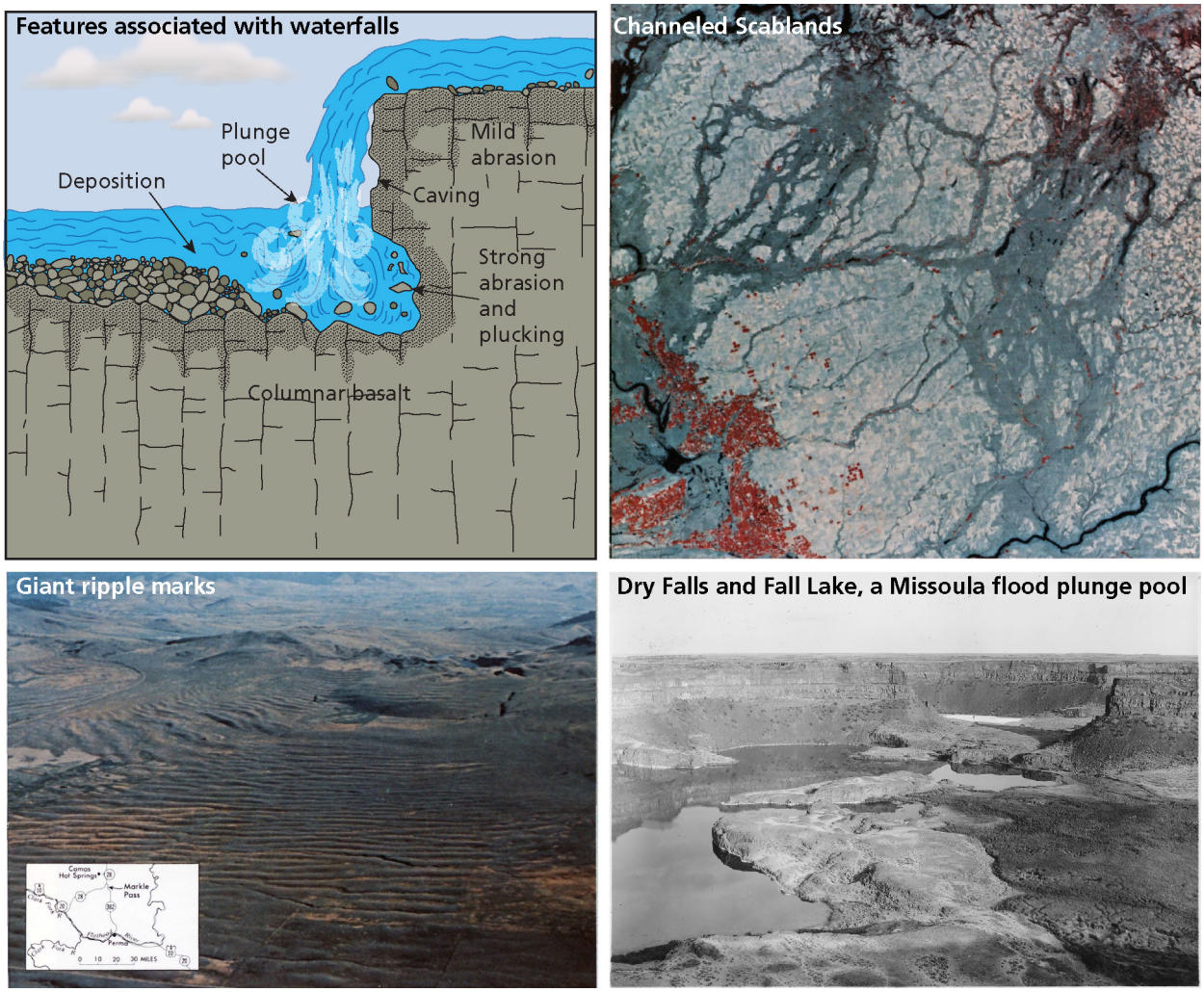

Figure 16. Features associated with the Glacial Lake Missoula floods. Upper left: Plunge pools form at the bases of waterfalls, which retreat upstream with lip undercutting and collapse. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after figure 19 in US Geological Survey (1973). Upper right: The Channeled Scablands cover about 34,252 km² (13,225 mi²) in eastern Washington. The photograph was taken by a NASA satellite at an altitude of 915 km (569 mi). The dark "braided" pattern depicts Missoula flood channels. Floodwaters eroded the lighter-colored loess, which now marks the uplands, and exposed the underlying darker basalt. The small red circles in the lower left are fields irrigated with rotating sprinklers. NASA image, extracted from US Geological Survey (1973, fig. 23). Lower left: Powerful currents formed giant ripple marks on Camas Prairie, Montana. US Geological Survey photograph from US Geological Survey (1973). Lower right: Fall Lake formed as a plunge pool at the base of Dry Falls in central Washington. Bureau of Reclamation photograph (from 1935), available at: http://commons.wikimedia.org/wiki/File:Dry_Falls,_near_Coulee_City,_Washington_-_NARA_-_294037.tif (accessed 29 July 2014).

column to form the top layers of many rhythmites. Flood-transported silt reached a maximum thickness of almost 12 m (39 ft) in an area north of the Walla Walla Valley (Busacca and McDonald 1994).

After the Floods: The Holocene

The last cataclysmic flood occurred approximately 15,000 years before present (Robert Carson, Whitman College, Phillips Professor of Geology and Environmental Studies, written communication, 23 January 2014). Faulting in the Columbia Basin continued in the Pleistocene, but no seismically active fault has been recognized in Holocene sediments. North–southcompression began to impact the Columbia Basin during the Miocene; the same stress pattern continues today, although the rate of deformation has declined since the mid-Miocene. Anticlines in the Yakima Fold Belt grow at an estimated rate of 0.04 mm (0.002 in) per year and basin subsidence occurs at an estimated rate of 3×10^{-3} mm (1×10^{-4} in) per year (Reidel et al. 1994).

Prior to the deluge, the Columbia River and its tributaries cut channels into the CRBG on their paths to the Pacific. Following the deluge, drainage networks formed the dry coulees that meander across eastern Washington and the Columbia Basin. Mill Creek flowed into the Walla Walla River, and both streams deposited alluvium and overbank deposits in the valley. Erosion subdued the topography and produced the rolling hills and terraces that form the region's present landscape.

The Columbia River flows past the sheer cliffs of Wallula Gap, which once held back the mighty floodwaters of Lake Missoula (fig. 17). Today, the relatively stable landscape of Whitman Mission National Historic Site contrasts sharply with the dynamic, turbulent past recorded in strata below the surface.

Figure 17. Wallula Gap. During the Missoula floods, this gap constricted the floodwaters and caused the formation of Lake Lewis. Photograph by Glenn Scofield Williams, available at http://commons.wikimedia.org/wiki/File:Ft._Nez_Perce_(Ft._Walla_Walla)_site.jpg (accessed 28 August 2013). Creative Commons Attribution 2.0 Generic (CC BY 2.0) license.

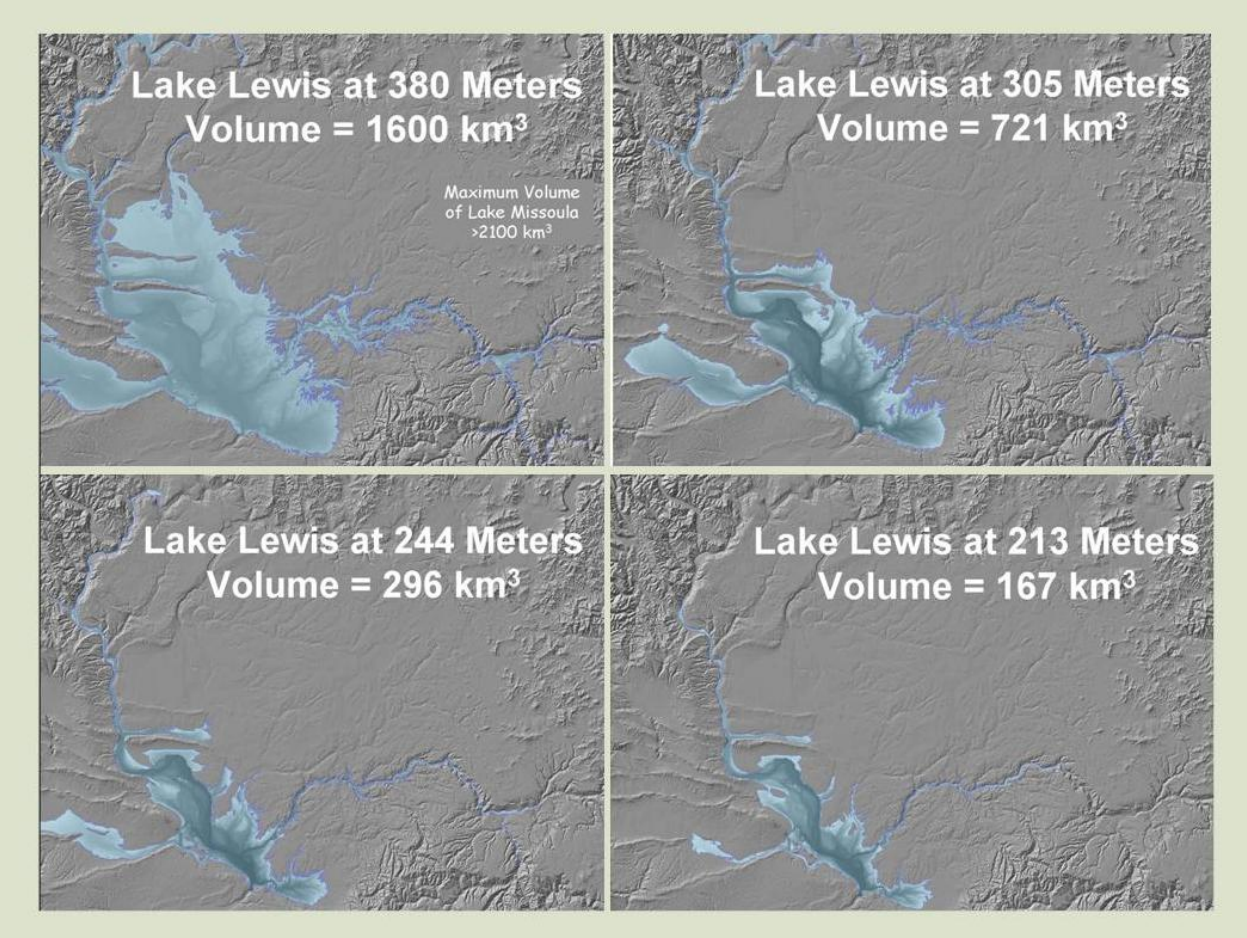

Figure 18. Lake Lewis at various levels following one of the Lake Missoula floods. Profiles by George V. Last, published by the US Department of Energy Pacific Northwest National Laboratory and available in the public domain at http://commons.wikimedia.org/wiki/File:Lake_Lewis_flood_profiles_.jpg (accessed 29 August 2013).

Geologic Map Data

This section summarizes the geologic map data available for Whitman Mission National Historic Site. A poster (in pocket) displays the map data draped over imagery of the park and surrounding area. The Map Unit Properties Table (in pocket) summarizes this report's content for each geologic map unit. Complete GIS data are included on the accompanying CD and are also available at the GRI publications website: http://go.nps.gov/gripubs.

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, these maps portray the spatial distribution and temporal relationships of rocks and unconsolidated deposits. Geologic maps can be divided into two primary types: surficial and 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.

Geologic maps often depict geomorphic features, structural interpretations (such as faults or folds), and locations of past geologic hazards that may be susceptible to future activity. 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.agiweb.org/environment/publications/mapping/index.html, provides more information about geologic maps and their uses.

Source Maps

The GRI team digitizes paper maps and converts digital data to conform to the GRI GIS data model. The GRI digital geologic map product includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, references, and figures. The GRI team used the following source to produce the digital geologic data set for Whitman Mission National Historic Site. This map also provided information for this report.

Derkey, R. E., D. F. Stradling, K. A. Lindsey, and T. L. Tolan. 2006. Geologic map of the College Place and Walla Walla 7.5-minute quadrangles, Walla Walla County, Washington, and Umatilla County, Oregon. Geologic Map GM-62 (scale 1:24,000). Washington Division of Geology and Earth Resources, Olympia, Washington.

Geologic GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available at http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for Whitman Mission National Historic Site using data model version 2.0. The GRI Geologic Maps website, http://www.nature.nps.gov/geology/inventory/geo_maps.cfm, provides more information about GRI map products.

GRI digital geologic data are included on the attached CD and are available through the NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/App/Reference/Search?SearchType=Q). Enter "GRI" as the search text and select a park from the unit list.

The following components and geology data layers are part of the data set:

- A GIS readme file (PDF) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information.
- Data in ESRI geodatabase and shapefile GIS formats
- Layer files with feature symbology (table 2)
- Federal Geographic Data Committee (FGDC)–compliant metadata
- An ancillary map information document (PDF) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures.
- An ESRI map document (.mxd) that displays the digital geologic data

Table 2. Geology data layers in the Whitman Mission National Historic Site GIS data.

Data Layer	Data Layer Code	On Poster?
Geologic Cross-Section Lines	sec	No
Mine Point Features (wells, borrow pits)	min	No
Geologic Sample Localities	gsl	No
Map Symbology	sym	Yes
Folds	fld	Yes
Faults	flt	Yes
Geologic Contacts	glga	Yes
Geologic Units	glb	Yes

GRI Map Poster

A poster of the GRI digital geologic data draped over a shaded relief image of the park and surrounding area is included with this report. Not all GIS feature classes are included on the poster (table 2). Geographic information and selected park features have been added to the poster. Digital elevation data and added geographic information are not included in the GRI GIS data set, but are available online from a variety of sources. Contact GRI for assistance locating these data.

Map Unit Properties Table

The Map Unit Properties Table lists the geologic time division, symbol, and a simplified description for each of the geologic map units in the GRI GIS data. Following the structure of the report, the table summarizes the geologic features, processes, resource management issues, and history associated with each map unit.

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 horizontally within 12 m (40 ft) of their true locations.

Glossary

This section contains brief definitions of selected geologic terms relevant to this report. Definitions are based on those in the American Geosciences Institute Glossary of Geology *(5th edition; 2005). Additional terms are defined at http://geomaps.wr.usgs.gov/parks/misc/glossarya.html.*

accretion. The gradual addition of new land to old by the deposition of sediment or emplacement of landmasses onto the edge of a continent at a convergent margin.

aeolian. Describes materials formed, eroded, or deposited by or related to the action of the wind.

alluvium. Stream-deposited sediment.

anticline. A convex-upward ("A" shaped) fold. Older rocks are found in the center.

ash (volcanic). Fine material ejected from a volcano.

axis (fold). A straight line approximation of the trend of a fold which divides the two limbs of the fold. "Hinge line" is a preferred term.

basalt. A dark-colored, often low-viscosity, extrusive igneous rock.

base level. The lowest level to which a stream can erode its channel. The ultimate base level for the land surface is sea level, but temporary base levels may exist locally.

basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie rocks exposed at the surface.

basin (structural). A doubly plunging syncline in which rocks dip inward from all sides.

basin (sedimentary). Any depression, from continental to local scales, into which sediments are deposited.

bed. The smallest sedimentary strata unit, commonly ranging in thickness from one centimeter to a meter or two and distinguishable from beds above and below.

bedding. Depositional layering or stratification of sediments.

bedrock. A general term for the rock that underlies soil or other unconsolidated, surficial material.

block (fault). A crustal unit bounded by faults, either completely or in part.

chemical sediment. A sediment precipitated directly from solution (also called nonclastic).

clast. An individual grain or rock fragment in a sedimentary rock, produced by the physical disintegration of a larger rock mass.

clastic. Describes rock or sediment made of fragments of pre-existing rocks (clasts).

clastic dike. A sedimentary dike consisting of a variety of clastic materials derived from underlying or overlying beds.

clay. Can be used to refer to clay minerals or as a sedimentary fragment size classification (less than 1/256 mm [0.00015 in]).

conglomerate. A coarse-grained, generally unsorted, sedimentary rock consisting of cemented, rounded clasts larger than 2 mm (0.08 in).

cordillera. A Spanish term for an extensive mountain range; used in North America to refer to all of the western mountain ranges of the continent.

craton. The relatively old and geologically stable interior of a continent (also see "continental shield").

cross section. A graphical interpretation of geology, structure, and/or stratigraphy in the third (vertical) dimension based on mapped and measured geological extents and attitudes depicted in a vertically oriented plane.

crust. Earth's outermost compositional shell, 10 to 40 km (6 to 25 mi) thick, consisting predominantly of relatively low-density silicate minerals (also see "oceanic crust" and "continental crust").

cutbank. A steep, bare slope formed by lateral erosion of a stream.

deformation. A general term for the processes of faulting, folding, and shearing of rocks as a result of various Earth forces such as compression (pushing together) and extension (pulling apart).

dip. The angle between a bed or other geologic surface and horizontal.

dip-slip fault. A fault with measurable offset where the relative movement is parallel to the dip of the fault.

downcutting. Stream erosion process in which the cutting is directed in primarily downward, as opposed to lateral erosion.

drainage basin. The total area from which a stream system receives or drains precipitation runoff.

eolian. Describes materials formed, eroded, or deposited by or related to the action of the wind. Also spelled "aeolian."

extension. A type of strain resulting from forces "pulling apart." Opposite of compression.

extrusive. Describes molten (igneous) material that has erupted onto Earth's surface.

fault. A break in rock along which relative movement has occurred between the two sides.

floodplain. The surface or strip of relatively smooth land adjacent to a river channel and formed by the river. Covered with water when the river overflows its banks.

fold. A curve or bend of an originally flat or planar structure such as rock strata, bedding planes, or foliation that is usually a product of deformation.

footwall. The mass of rock beneath a fault surface (also see "hanging wall").

formation. Fundamental rock-stratigraphic unit that is mappable, lithologically distinct from adjoining strata, and has definable upper and lower contacts.

fracture. Irregular breakage of a mineral. Any break in a rock (e.g., crack, joint, fault).

geology. The study of Earth including its origin, history, physical processes, components, and morphology.

hanging wall. The mass of rock above a fault surface (also see "footwall").

hot spot. A volcanic center that is thought to be the surface expression of a rising plume of hot mantle material.

igneous. Refers to a rock or mineral that originated from molten material; one of the three main classes of rocks—igneous, metamorphic, and sedimentary.

incision. The process whereby a downward-eroding stream deepens its channel or produces a narrow, steep-walled valley.

jökulhlaup. An Icelandic term for glacier outburst flood.

lacustrine. Pertaining to, produced by, or inhabiting a lake or lakes.

lava. Still-molten or solidified magma that has been extruded onto Earth's surface though a volcano or fissure.

left lateral fault. A strike slip fault on which the side opposite the observer has been displaced to the left Synonymous with "sinistral fault."

limb. Either side of a structural fold.

lineament. Any relatively straight surface feature that can be identified via observation, mapping, or remote sensing, often reflects crustal structure.

lithology. The physical description or classification of a rock or rock unit based on characters such as its color, mineral composition, and grain size.

loess. Windblown silt-sized sediment, generally of glacial origin.

magma. Molten rock beneath Earth's surface capable of intrusion and extrusion.

marker bed. A distinctive layer used to trace a geologic unit from one geographic location to another.

meander. Sinuous lateral curve or bend in a stream channel. An entrenched meander is incised, or carved downward into the surface of the valley in which a meander originally formed. The meander preserves its original pattern with little modification.

member. A lithostratigraphic unit with definable contacts; a member subdivides a formation.

meta–. A prefix used with the name of a sedimentary or igneous rock, indicating that the rock has been metamorphosed.

metamorphism. Literally, a change in form. Metamorphism occurs in rocks through mineral alteration, formation, and/or recrystallization from increased heat and/or pressure.

normal fault. A dip-slip fault in which the hanging wall moves down relative to the footwall.

oblique fault. A fault in which motion includes both dip-slip and strike-slip components (also see "dip-slip fault" and "strike-slip fault").

oceanic crust. Earth's crust formed at spreading ridges that underlies the ocean basins. Oceanic crust is 6 to 7 km (3 to 4 miles) thick and generally of basaltic composition.

outcrop. Any part of a rock mass or formation that is exposed or "crops out" at Earth's surface.

outwash. Glacial sediment transported and deposited by meltwater streams.

overbank deposit. Alluvium deposited outside a stream channel during flooding.

oxbow. A closely looping stream meander resembling the U-shaped frame embracing an ox's neck; having an extreme curvature such that only a neck of land is left between two parts of the stream.

pebble. Generally, small rounded rock particles from 4 to 64 mm (0.16 to 2.52 in) in diameter.

plate tectonics. The concept that the lithosphere is broken up into a series of rigid plates that move over Earth's surface above a more fluid asthenosphere.

plateau. A broad, flat-topped topographic high (terrestrial or marine) of great extent and elevation above the surrounding plains, canyons, or valleys.

point bar. A low ridge of sand and gravel deposited in a stream channel on the inside of a meander where flow velocity slows.

radiometric age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products.

reverse fault. A contractional high-angle (greater than 45°) dip-slip fault in which the hanging wall moves up relative to the footwall (also see "thrust fault").

ripple marks. The undulating, approximately parallel and usually small-scale ridge pattern formed on sediment by the flow of wind or water.

rip-up clast. A mud clast (usually of flat shape) that has been "ripped up" by currents from a semiconsolidated mud deposit, transported, and deposited elsewhere. Often associated with storms or other high-energy events.

sand. A clastic particle smaller than a granule and larger than a silt grain, having a diameter in the range of 1/16 mm (0.0025 in) to 2 mm (0.08 in).

sandstone. Clastic sedimentary rock of predominantly sand-sized grains.

sediment. An eroded and deposited, unconsolidated accumulation of rock and mineral fragments.

sedimentary rock. A consolidated and lithified rock consisting of clastic and/or chemical sediment(s). One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

shale. A clastic sedimentary rock made of clay-sized particles that exhibit parallel splitting properties.

silt. Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay (1/256 to 1/16 mm [0.00015 to 0.002 in]).

siltstone. A variably lithified sedimentary rock composed of silt-sized grains.

slope. The inclined surface of any geomorphic feature or measurement thereof. Synonymous with "gradient."

steptoe. An isolated hill or mountain of older rock that projects above a surrounding lava field.

strata. Tabular or sheet-like masses or distinct layers of rock.

stratification. The accumulation, or layering of sedimentary rocks in strata. Tabular, or planar, stratification refers to essentially parallel surfaces. Cross-stratification refers to strata inclined at an angle to the main stratification.

stream. Any body of water moving under gravity flow in a clearly confined channel.

stream channel. A long, narrow depression shaped by the concentrated flow of a stream and covered continuously or periodically by water.

strike-slip fault. A fault with measurable offset where the relative movement is parallel to the strike of the fault. Said to be "sinistral" (left-lateral) if relative motion of the block opposite the observer appears to be to the left. "Dextral" (right-lateral) describes relative motion to the right.

structure. The attitude and relative positions of the rock masses of an area resulting from such processes as faulting, folding, and igneous intrusions.

subaerial. Describes conditions and processes that exist or operate in the open air on or immediately adjacent to the land surface.

subduction zone. A convergent plate boundary where oceanic lithosphere descends beneath a continental or oceanic plate and is carried down into the mantle.

subsidence. The gradual sinking or depression of part of Earth's surface.

suture. The linear zone where two continental landmasses become joined via obduction.

syncline. A downward curving (concave-up) fold with layers that dip inward; the core of the syncline contains the stratigraphically-younger rocks.

tectonic. Relating to large-scale movement and deformation of Earth's crust.

tephra. A collective term used for all pyroclastic material, regardless of size, shape, or origin, ejected during an explosive volcanic eruption.

terrace. A relatively level bench or step-like surface breaking the continuity of a slope (also see "stream terrace").

terrane. A large region or group of rocks with similar geology, age, or structural style.

terrestrial. Relating to land, Earth, or its inhabitants.

terrigenous. Derived from the land or a continent.

thrust fault. A contractional dip-slip fault with a shallowly dipping fault surface (less than 45°) where the hanging wall moves up and over relative to the footwall.

topography. The general morphology of Earth's surface, including relief and locations of natural and anthropogenic features.

unconformity. An erosional or non-depositional surface bounded on one or both sides by sedimentary strata. An unconformity marks a period of missing time.

volcanic. Describes anything related to volcanoes. Can refer to igneous rock crystallized at or near Earth's surface (e.g., lava).

volcaniclastic. Describes clastic volcanic materials formed by any process of fragmentation, dispersed by any kind of transporting agent, deposited in any environment.

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Additional References

This section lists additional references, resources, and websites that may be of use to resource managers. Web addresses are valid as of July 2014. Refer to the appendix for laws, regulations, and policies that apply to NPS geologic resources.

Geology of National Park Service Areas

NPS Geologic Resources Division (Lakewood, Colorado): http://nature.nps.gov/geology/

NPS Geologic Resources Inventory: http://www.nature.nps.gov/geology/inventory/index.cfm.

NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program: http://www.nature.nps.gov/geology/gip/index.cfm

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://www.nature.nps.gov/views/

NPS Resource Management Guidance and Documents

1998 National parks omnibus management act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf

Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html

NPS-75: Natural resource inventory and monitoring guideline: http://www.nature.nps.gov/nps75/nps75.pdf

NPS Natural resource management reference manual #77: http://www.nature.nps.gov/Rm77/

Geologic monitoring manual (Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado): http://nature.nps.gov/geology/monitoring/index.cfm

NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://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://globalchange.gov/home

Intergovernmental Panel on Climate Change: http://www.ipcc.ch/

Geological Surveys and Societies

Washington State Division of Geology and Earth Resources: http://www.dnr.wa.gov/researchscience/geologyearthsciences/pages/home.aspx

US Geological Survey: http://www.usgs.gov/

Geological Society of America: http://www.geosociety.org/

American Geophysical Union: http://sites.agu.org/

American Geosciences Institute: http://www.agiweb.org/

Association of American State Geologists: http://www.stategeologists.org/

US Geological Survey Reference Tools

National geologic map database (NGMDB): http://ngmdb.usgs.gov/

Geologic names lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html

Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/

GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")

Publications warehouse (many publications available online): http://pubs.er.usgs.gov

Tapestry of time and terrain (descriptions of physiographic provinces): http://tapestry.usgs.gov/Default.html

Appendix: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to National Park Service minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of July 2014. Contact the NPS Geologic Resources Division for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Rocks and Minerals	**NPS Organic Act**, **16 USC § 1 *et seq.*** directs the NPS to conserve all resources in parks (including rock and mineral resources), unless otherwise authorized by law. **Exception: 16 USC § 445c (c) – Pipestone National Monument enabling statute**. Authorizes American Indian collection of catlinite (red pipestone).	**36 CFR § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units. **Exception: 36 CFR § 7.91** allows limited gold panning in Whiskeytown. **Exception: 36 CFR § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, or Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
Park Use of Sand and Gravel	**Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units. **Exception:** 16 USC §90c 1(b) the non-wilderness portion of Lake Chelan National Recreation Area, where sand, rock and gravel may be made available for sale to the residents of Stehekin for local use as long as such sale and disposal does not have significant adverse effects on the administration of the National Recreation Area.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: -only for park administrative uses; -after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment; -after finding the use is park's most reasonable alternative based on environment and economics; -parks should use existing pits and create new pits only in accordance with park-wide borrow management plan; -spoil areas must comply with **Part 6** standards; 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
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).

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

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.

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National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

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