National Park Service
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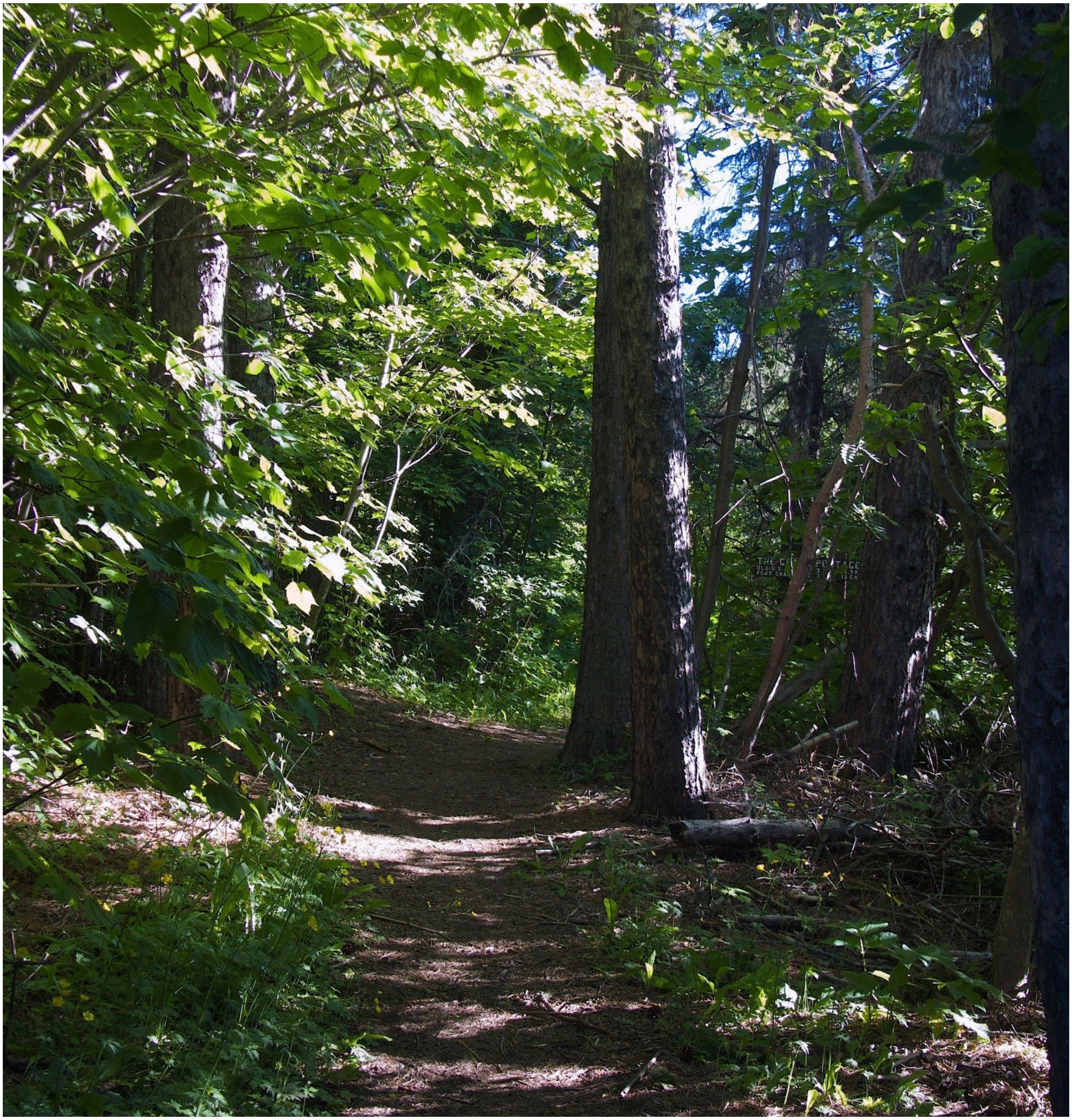
Natural Resource Stewardship and Science

Grand Portage National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2019/2025



ON THE COVER
Photograph of the historic depot and dock on Grand Portage Bay at Lake Superior. Hat Point and Pete's Island are in the distance. Isle Royale is just visible on the horizon.
National Park Service photograph (Grand Portage National Monument).

THIS PAGE
Photograph of the Grand Portage trace. The Grand Portage corridor goes through the thick woods of the monument area. In the late 1790s, the path was the gateway to northwestern Canada's fur trade. Every summer voyageurs carried tons of furs down the treacherous and slippery path and tons of trade goods back up the portage around rapids of the Pigeon River.
National Park Service photograph (Grand Portage National Monument).

Grand Portage National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2019/2025

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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.

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

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

This report is available from the http://go.nps.gov/gripubs, and the https://www.nps.gov/im/publication-series.htm. If you have difficulty accessing information in this publication, particularly if using assistive technology, please email irma@nps.gov

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Executive Summary

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

This report synthesizes discussions from a scoping meeting held in 2010 and a follow-up conference call in 2018 (see Appendix A). Chapters of this report discuss the geologic setting, distinctive geologic features and processes within Grand Portage National Monument, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the previously completed GRI map data. A poster (in pocket) illustrates these data.

Billion-year-old intrusions of durable diabase rock into softer, older metasedimentary rock caused the eventual formation of rapids and falls on the Pigeon River—the gateway for North American fur trade. These rapids could not be passed by fur-laden canoes or other watercraft necessitating an overland portage to transport fur downriver and trade goods upriver. The 13.7-km (8.5 mi) Grand Portage, known as the Gitchi Onigaming (Great Carrying Place) by the Ojibwe people, allowed this passage between western Lake Superior at Grand Portage Bay and Fort Charlotte at the navigable Pigeon River. Grand Portage National Monument's bedrock records a geologic history beginning more than 1.7 billion years ago when much of northern Minnesota was underwater as an embayment in a marine basin; fine-grained sediments accumulated in this basin to later become the Rove Formation. An ancient orogeny sutured together landmasses and metamorphosed the Rove Formation. Compression turned to extension as a mid-continent rift developed more than 1 billion years ago. In one phase of the failed rift, the notable Pigeon River Diabase intruded along dikes throughout the Rove Formation. These rocks remained buried for millennia prior to the glaciations of the Pleistocene more than 10,000 years ago. During these glaciations, vast continental ice sheets descended south from Canada and covered the landscape with ice. These advances scoured the softer Rove Formation into valleys that filled with glacial sediment, leaving the diabase as ridges. This setting caused the glaciers to leave a complex record of glacial and related deposits on the local landscape. When weight of glacial ice was gone, the Earth's surface rebounded upwards. A series of glacial lakes filled the Superior basin until modern conditions established the monument's landscape. Earth surface processes continue to modify and affect the Grand Portage landscape. Geology and geologic processes affect nearly every facet of the natural environment of the monument as well as its long and rich human history.

This report is supported by two GRI-compiled datasets of the bedrock geology and some postglacial features of Grand Portage National Monument. Surficial geologic mapping was not included. The geology inside the monument's boundaries is included with bedrock coverage of the greater Duluth Complex by Miller et al. (2001), four-letter map code "grpo." Glacial-lake terrace traces and areas are also part of this dataset by Rosenthal (2012). Geology of the nearby Pigeon Point 7.5-minute quadrangle (Mudrey 1977) is included as four-letter map code "pipo." The map data poster (in pocket) is the primary figure of this GRI report, showing the GRI GIS data (grpo) draped over shaded relief imagery of the park. Individual bedrock units and terrace areas are included in the poster legend.

The monument's geologic features, processes, and management issues are outlined and described. These include:

- Shoreline erosion
- Fluvial features and processes
- Geologic hazards: slope movements and earthquakes
- Disturbed lands
- Potential energy and mineral development
- Glacial features and lake stages
- Faults
- Ancient bedrock: sedimentary features, polarity reversals, and volcanic features
- Paleontological resource inventory, monitoring, and protection

This report provides a detailed look at which features, processes, and/or issues pertain to each map unit included in the GRI GIS data. Geologic resource management information is provided that includes relevant references and links to data and resources for park managers to provide guidance in making science-based decisions. Additional tables highlight the GRI GIS data layers for the separate map products: grpo_geology.mxd and pipo_geology.mxd.

Products and Acknowledgments

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

GRI Products

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

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

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

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

Acknowledgments

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Figure 1. Maps of Grand Portage National Monument.
Top image shows the location of the Grand Portage as part of the trading route used in the 1700s. Bottom image is the monument today, gracing the shores of Lake Superior. National Park Service maps available from the Harpers Ferry Center at https://www.nps.gov/subjects/hfc/index.htm.

Geologic Setting, History, and Significance

This chapter describes the regional geologic setting and history of the monument and summarizes connections among geologic resources, other monument resources, and monument stories.

Monument Establishment

Trekking the 13.7-km (8.5 mi) portage, known as the Gitchi Onigaming (Great Carrying Place) by the Ojibwe people, between western Lake Superior at Grand Portage Bay and Fort Charlotte at the navigable Pigeon River allows one to appreciate the fortitude with which Native Americans developed a portage and trade network that early European explorers and traders later used to gain access into the wilderness and seek their fortunes from the natural bounty therein (National Park Service 2017). Originally established as a national historic site on September 15, 1951, Grand Portage National Monument (fig. 1) was designated on September 2, 1958 (P. L. 85-910, 72 Stat. 1751; Cockrell 1983). It is the earliest fur trading site in the national park system. Monument staff also collaborates with the Grand Portage Band of Lake Superior Chippewa (Ojibwe) in preserving and interpreting the heritage and traditions of the Ojibwe people (Hunt et al. 2008; National Park Service 2017). It commemorates and preserves a portion of the 18th century fur trade route (between 1731 and 1804) that led to international commerce and exploration, as well as contact between Ojibwe and other Native American societies and the North West Company partners (fig. 2), clerks, and canoe men. The Grand Portage trail remains an international road, which under the terms of the Webster-Ashburton Treaty of 1842, allows the use of the trail freely to citizens of both the US and Canada (National Park Service 2017). The monument encompasses 287 ha (710 ac) of land in Cook County, northern Minnesota near the US border with Ontario, Canada (fig. 3) and attracts more than 110,000 visitors annually (Kraft et al. 2014). As a long skinny tract of land, the monument includes between 30 and 90 m (100 and 300 ft) on either side of the historic portage trace itself, all within both the Grand Portage Indian Reservation and the unincorporated community of Grand Portage. The monument is bordered to the east by Lake Superior, to the north and south by the Grand Portage Indian Reservation, and to the west by the Pigeon River and Ontario, Canada (National Park Service 2017).

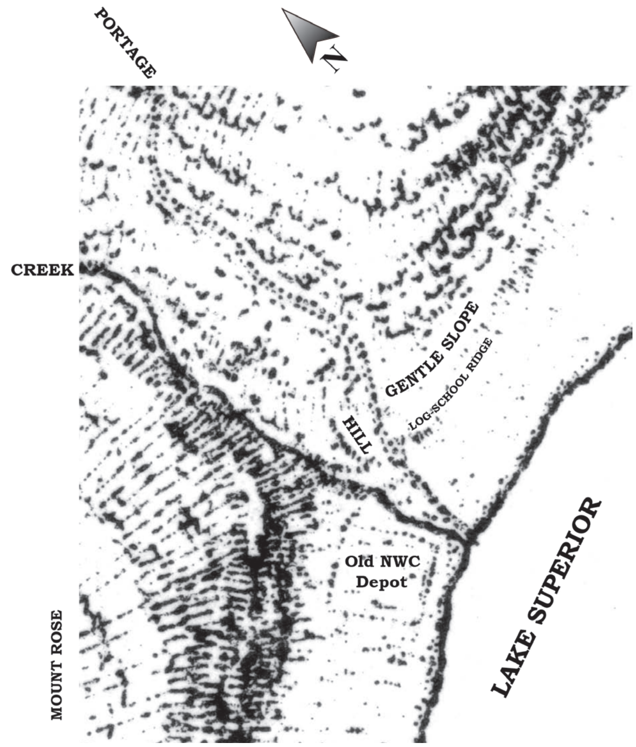


Figure 2. Annotated historic map of the Grand Portage shoreline.
Original map was by Whistler in the 1820s. NWC stands for North West Company. The Grand Portage ascended from the shore to higher ground (probably underlain by PCprdb) on the approximate course of today's Upper Road on the east side of the church hill. Graphic is annotated as figure 25 in Birk (2006).

Geologic Setting and History

Grand Portage National Monument sits amidst some of the oldest bedrock in North America. The bedrock here consists primarily of Paleoproterozoic slaty rocks of the Rove Formation (geologic map unit **PCrv**), a thick sequence of weakly metamorphosed muddy sedimentary rocks that were deposited in a large bowl, known as the Animikie basin, which currently spans the area from Duluth to the Canadian border. The Animikie basin formed in front of a collisional mountain-building event known as the Penokean Orogeny that occurred 1.88 to 1.83 billion years ago during the Paleoproterozoic Era (table 1 and fig. 4A). This event involved collisions between early landmasses that now make up part of the North American craton or ancient "core" of the continent (Schulz and Cannon 2007). As the Penokean mountains (in an area currently occupied by central Minnesota) were uplifted they were also undergoing rapid erosion, with the sediment being

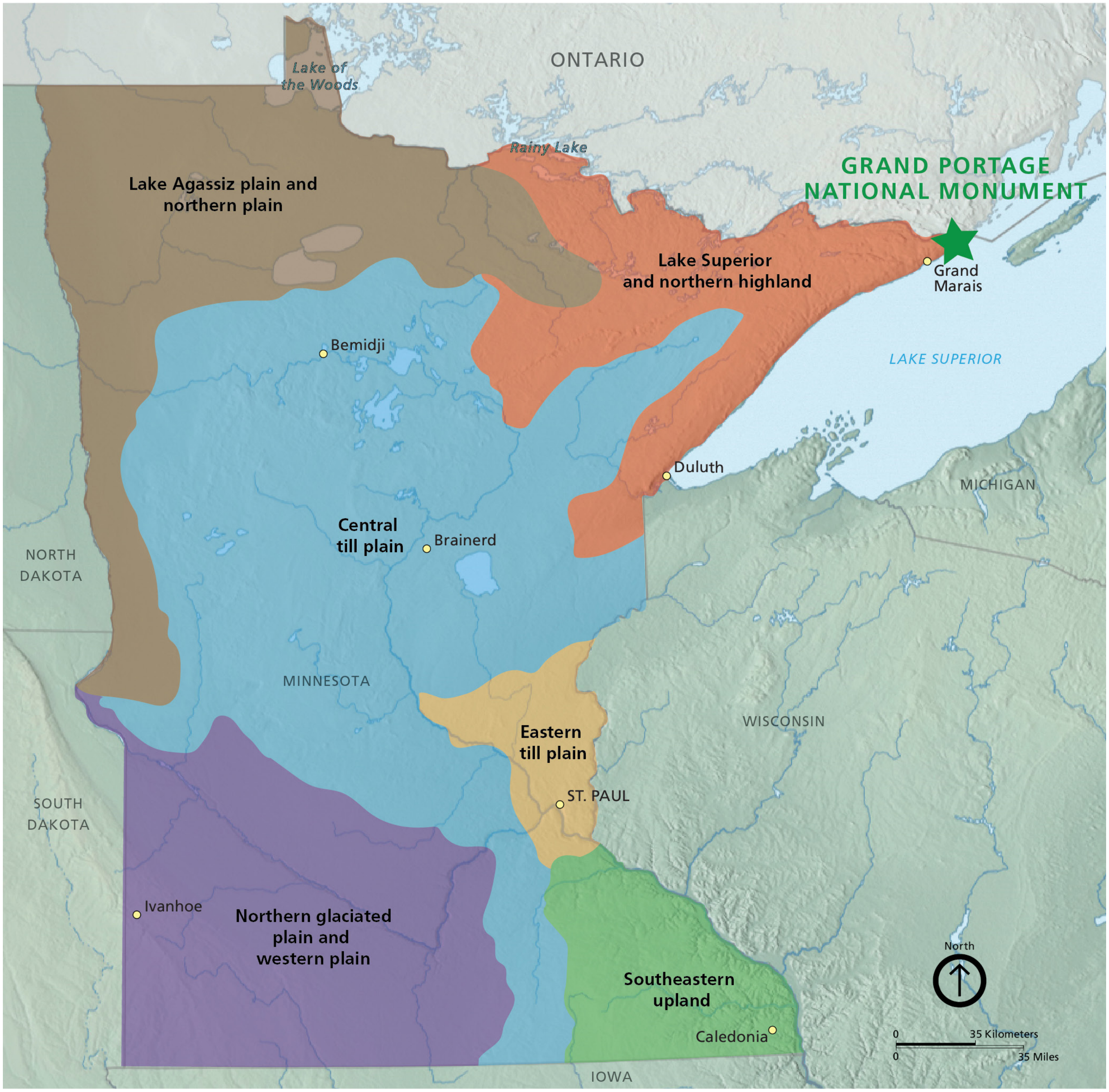


Figure 3. Physiographic region map.
Grand Portage National Monument (green star) is within the Lake Superior and northern highland region. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Ojakangas and Matsch (1982), Martin (1916), the Wisconsin Geological and Natural History Survey, and US Environmental Protection Agency (2007). Shaded relief base map by Tom Patterson (National Park Service).

carried into and deposited in the Animikie basin until about 1.78 billion years ago (Schulz and Cannon 2007); this sediment now forms the Rove Formation.

Around 1.1 billion years ago, during the Mesoproterozoic era, formation of the midcontinent rift (fig. 4B) allowed molten magma to work its way up from the Earth's mantle through fractures in the Earth's crust. Some of this magma made it all the way to the surface, where it erupted and formed the many lava flows found rimming Lake Superior, but some of it cooled in place beneath the surface to form dikes (cut across preexisting fabrics in country rocks) and sills (subhorizontal bodies more or less congruent with the

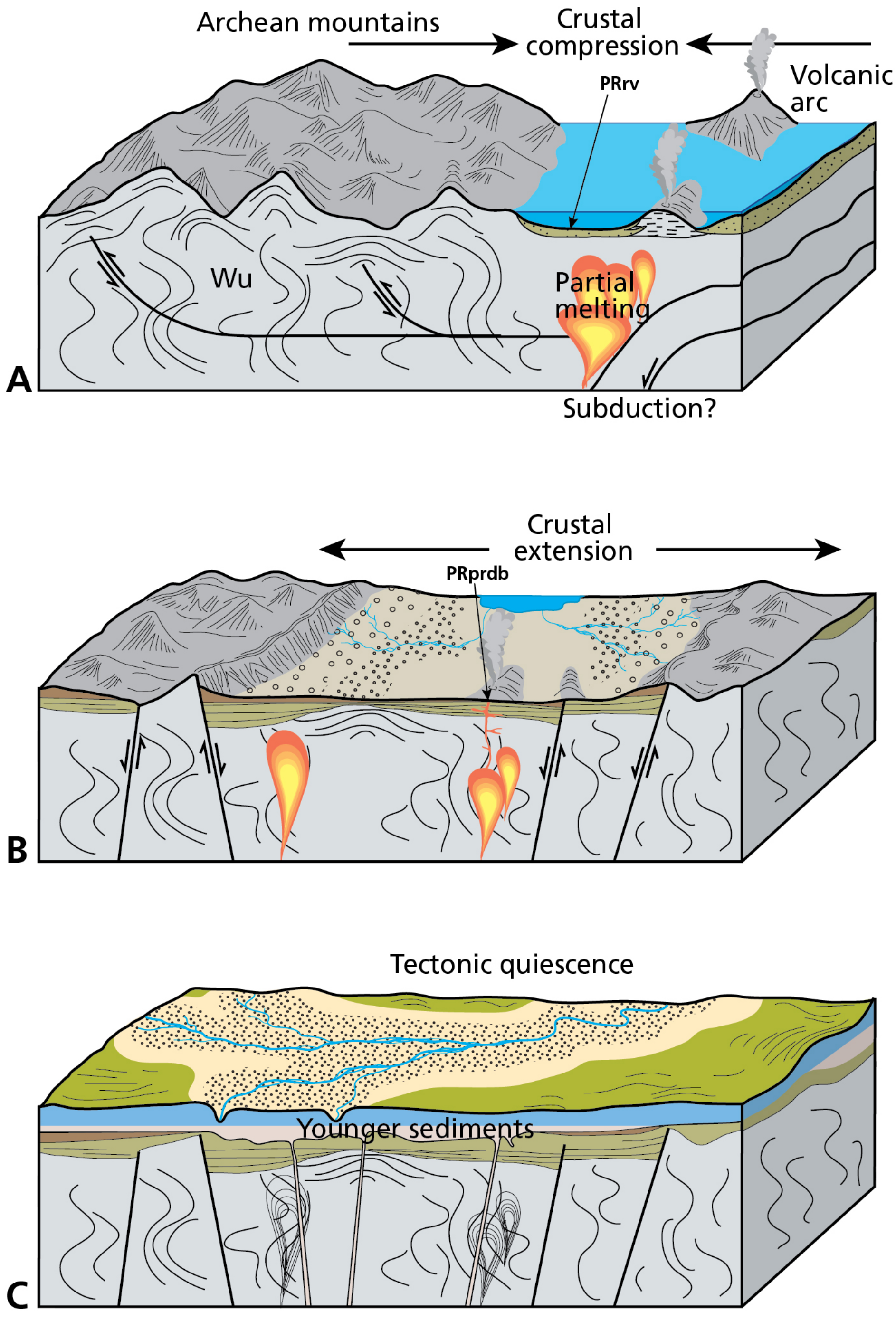
Table 1. Geologic time scale.

The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. Only geologic units mapped within the monument are included. Age ranges are millions of years ago (MYA). National Park Service graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale).

Unit of Geologic Time	MYA	Geologic Map Units	Local Geologic Events
Cenozoic Era (CZ), Quaternary Period (Q), Holocene Epoch (H)	0.01–today	Modern alluvium and colluvium (not mapped)	Human history; modern surficial units reworked Shoreline change Continued erosion, stream incision
Cenozoic Era (CZ), Quaternary Period (Q), Pleistocene Epoch (PE)	2.6–0.01	Paleoshorelines, lake terrace areas, and terrace areas formed	Lake Superior formed Global glaciations; periglacial conditions
Cenozoic Era (CZ), Tertiary: Neogene Period (N)	23.0–2.6	None mapped	Continued erosion and mass wasting
Cenozoic Era (CZ), Tertiary: Paleogene Period (PG)	66.0–23.0	None mapped	Continued erosion and mass wasting
Mesozoic Era (MZ)	251.9–66.0	None mapped	Erosion Atlantic Ocean opens Breakup of Pangea
Paleozoic Era (PZ)	541.0–251.9	None mapped	Supercontinent Pangea intact Erosion and weathering of overlying sediments
Neoproterozoic Era (Z)	1,000–541	PCprdb intruded	Supercontinent Rodinia rifted apart Burial and deformation of rift deposits Lake Superior basin coalesced
Mesoproterozoic Era (Y)	1,600–1,000	None mapped	Midcontinent rift became inactive; basins subsided Volcanism ceased, erosion Widespread volcanism in rift Midcontinent rift began to open; Lake Superior basin developed
Paleoproterozoic Era (X)	2,500–1,600	PCrv deposited	Uplift, volcanism, widespread erosion
Archean Eon	~4,000–2,500	None mapped	Granitic crust formed, metamorphism
Hadean Eon	4,600–4,000	None mapped	Formation of Earth's crust Oldest known Earth rocks

country rock fabric) of igneous rocks such as diabase. The diabase dikes (a dark, crystalline igneous rock) intruded the older Rove Formation in two pulses during the midcontinent rift event. The oldest dikes are known as the Grand Portage dike swarm and are generally east-trending features up to 45 m (150 ft) thick. Slightly younger dikes of the Pigeon River (**PCprdb**) swarm are much more voluminous (Miller et al. 2001). The dikes form a roughly orthogonal array of prominent, linear northeast- and northwest-trending bodies.

The midcontinent rift is a major tectonic feature that stretches from Kansas through the Lake Superior region, and into southern Michigan (fig. 5). The rift developed in several stages over some 80 million years from around 1.14 billion years ago to 1.06 billion years ago (fig. 6). The first stage was the initial rifting of the

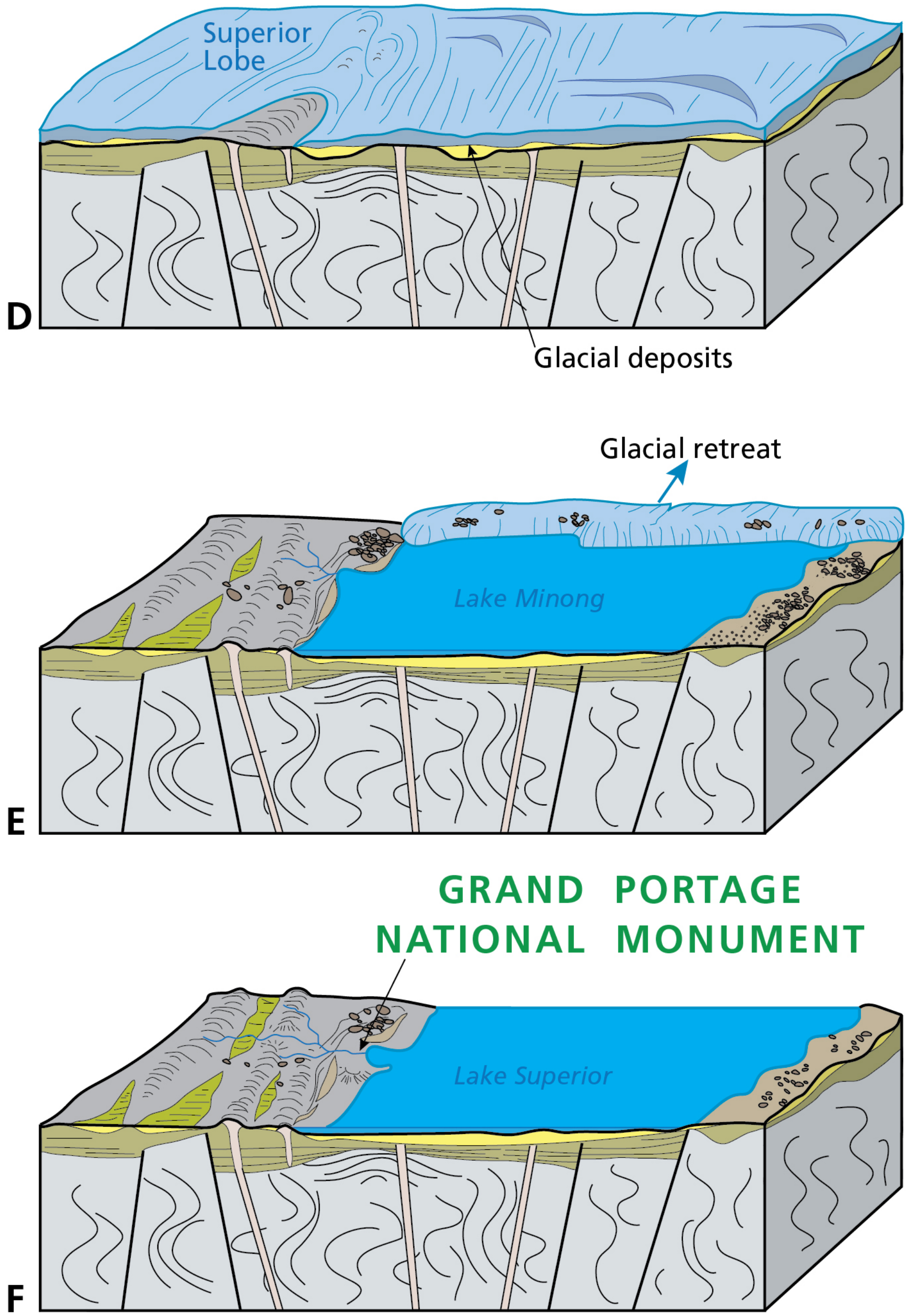


2.5 billion to 1.6 billion years ago: The North American craton formed in a series of igneous and metamorphic events. Sediments collected in basins, including the Rove Formation.

1.14 billion to 1.0 billion years ago: Crustal extension formed a rift in the the North American craton. The Keweenawan Supergroup of layered volcanics and sediments was deposited in the rift valley. Late in the history of the rift, diabase dikes intruded the older Rove Formation and any younger Mesoproterozoic rocks.

760 million to 66 million years ago: Deposition of younger sediments buried the Midcontinent rift.
Local streams and rivers eroded deeply into the overlying sediments.

Figure 4A–C. Schematic graphics illustrating the evolution of the Grand Portage National Monument landscape.
Graphics are not to scale. Graphics by Trista L. Thornberry-Ehrlich (Colorado State University).



66 million to 12,000 years ago: Erosion and weathering exposed the resistant diabase dikes as local ridges. During the Pleistocene, glaciers scoured the landscape several times and left thick deposits of till, outwash, and lake deposits.

10,000 years ago: As the glaciers retreated, a series of glacial lakes occupied the Superior Basin at various elevations leaving perched or inundated shoreline features and deposits. The land was rebounding after the removal of the weight of the ice. Modern rivers began to incise their channels through the glacial and lake sediment.

Present day: *Lake Superior* fills the basin scoured by the glaciers. The Grand Portage was weathered as a gap through the diabase ridges. Marshes and swamps occupy the lower areas between the ridges. Lake levels fluctuate causing changes in the morphology of shorelines.

Figure 4D–F. Schematic graphics illustrating the evolution of the Grand Portage National Monument landscape, continued.
Graphics are not to scale. Graphics by Trista L. Thornberry-Ehrlich (Colorado State University).

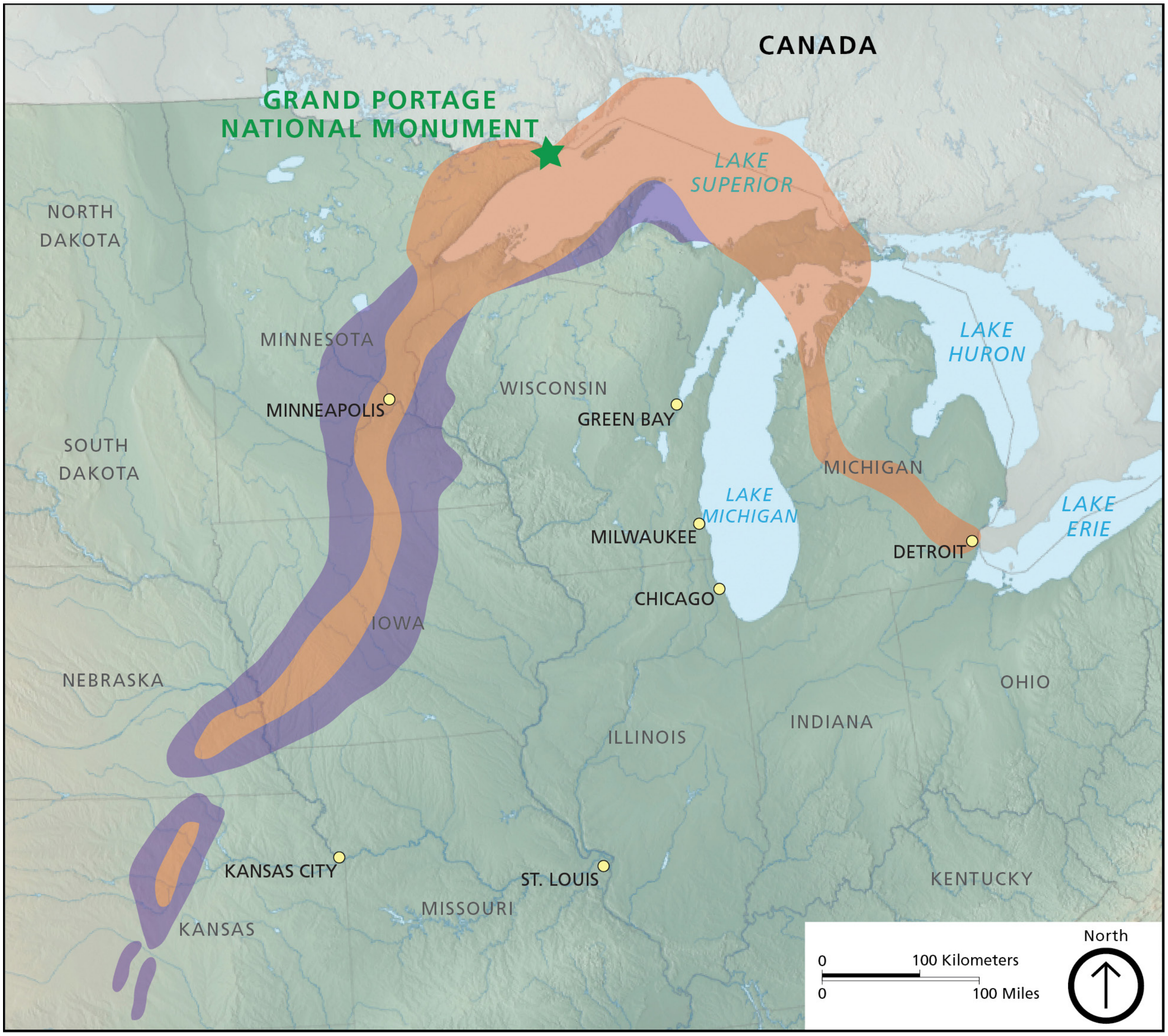
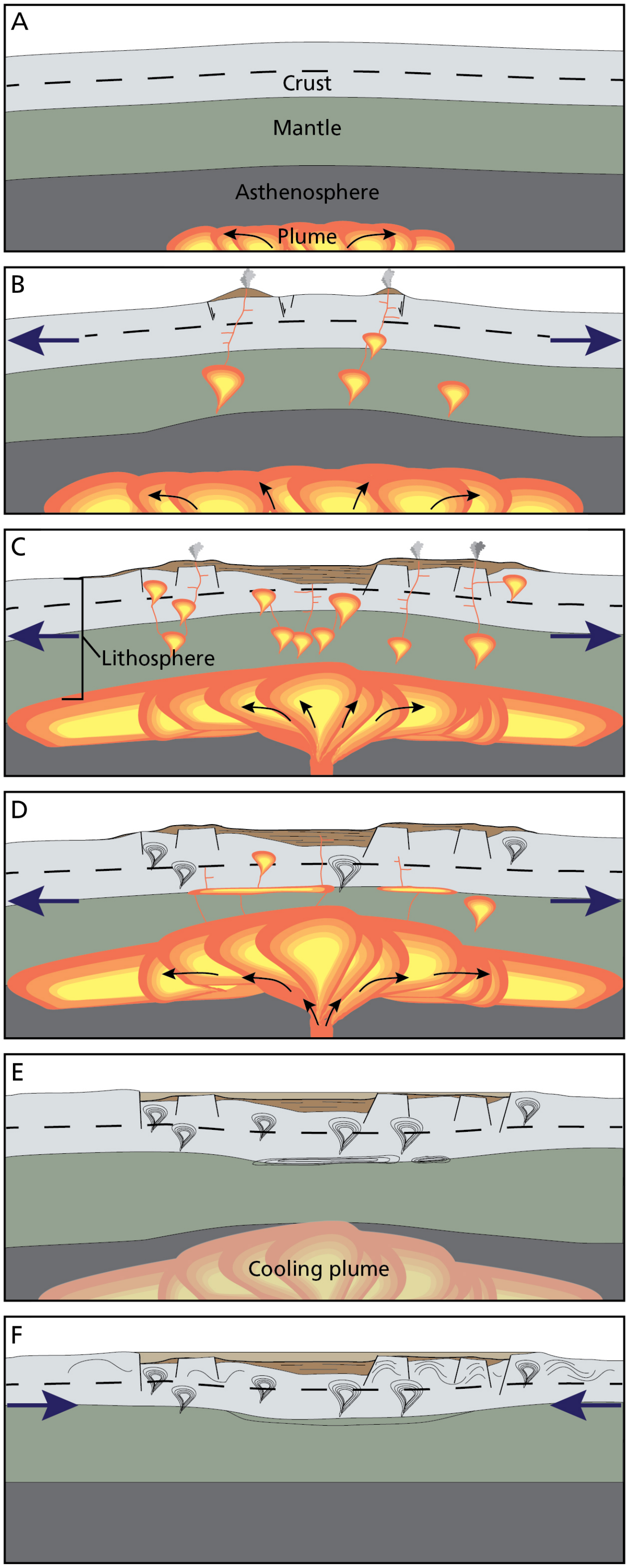


Figure 5. Map of the midcontinent rift.
Orange areas delineate the primary volcanic basins with associated sedimentary and plutonic rocks. The purple areas represent primarily late-stage sedimentary rocks deposited after volcanism had ceased. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Hinze et al. (1997, figure 3). Shaded relief base map by Tom Patterson (National Park Service).



A: 1.110 billion years ago: Rifting initiated with a broad, domal uplift over a rising asthenospheric plume.

B: 1.108 billion years ago: Extension reached a point where thinning of the crust and upper mantle occurred. Mantle plumes began to rise and supplied lava to volcanoes on the surface.

C: 1.100 billion years ago: The top of the plume reached the base of the lithosphere and spread out laterally. Grabens developed in the rift axis. Massive volumes of lava extruded onto the surface.

D: 1.094 billion years ago: The plume continued to spread laterally and became the dominant source of lava for volcanic flows and igneous intrusions. Grabens continued to develop.

E: 1.080 billion years ago: The cooling plume dragged the attached lithosphere downward. The added weight of lavas and sediments contributed to sagging.

F: 1.060 billion years ago: After extension ceased, compression, possibly from the Grenville Orogeny to the east, reactivated zones of weakness and caused regional folding. Rift area became part of the supercontinent, Rodinia.

Figure 6. Evolution of the midcontinent rift.
The rift developed in a series of events: A–F. Large arrows indicate the tectonic stress direction (e.g., extension or compression). Schematic graphics are not to scale and do not represent any particular cross section through the rift. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Hinze et al. (1997, figure 19).

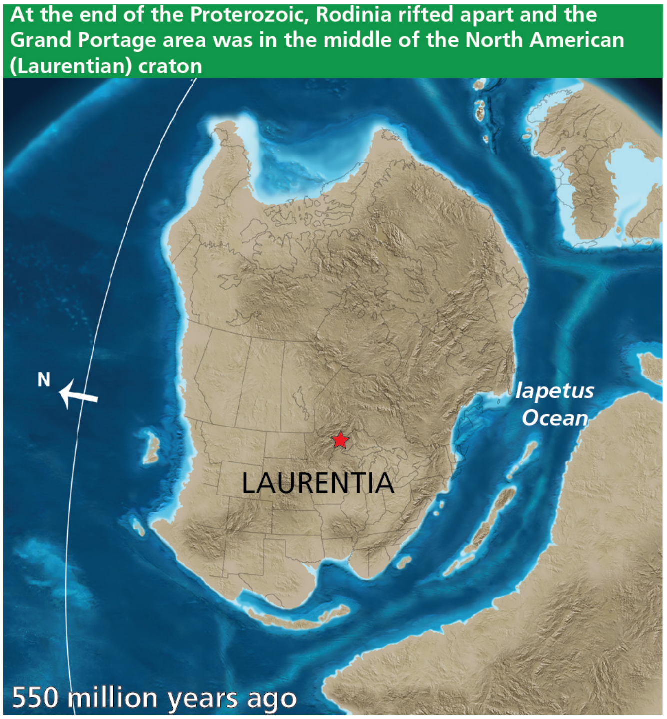


Figure 7. Paleogeographic map of North America 550 million years ago.
At this time, the Proterozoic supercontinent, Rodinia, was rifted apart and northern Minnesota was in the center of the North American (Laurentian) craton. The Paleoproterozoic sediments and Neoproterozoic volcanics were deeply buried. Red star indicates approximate present-day location of Grand Portage National Monument. Graphic compiled by Trista L. Thornberry-Ehrlich (Colorado State University). Base paleogeographic map is from "North American Key Time Slices" © 2013 Colorado Plateau Geosystems Inc., used under license.

continental rocks and accompanying volcanism. The rift developed as a central graben or downdropped "sag" basin bounded on either side by normal faults. Following the end of significant volcanism, the second stage was continued sagging within the rift because of thermal subsidence, with accompanying sediment collecting in the basin and no volcanism. In the deepest part of the rift beneath Lake Superior, rift rocks have been imaged nearly to the Moho (the Mohorovičić discontinuity, the boundary between the Earth's crust and the mantle) at 30 km (19 mi) depth, with about 20 km (12 mi) of basalt flows overlain by about 10 km (6 mi) of sediment. The third stage in midcontinent rift history occurred when the stretching or extensional nature of the rift changed to compression at the onset of the Grenville Orogeny (mountain building event) to the east of the rift along the eastern margin of ancient North America. This late-stage compressional

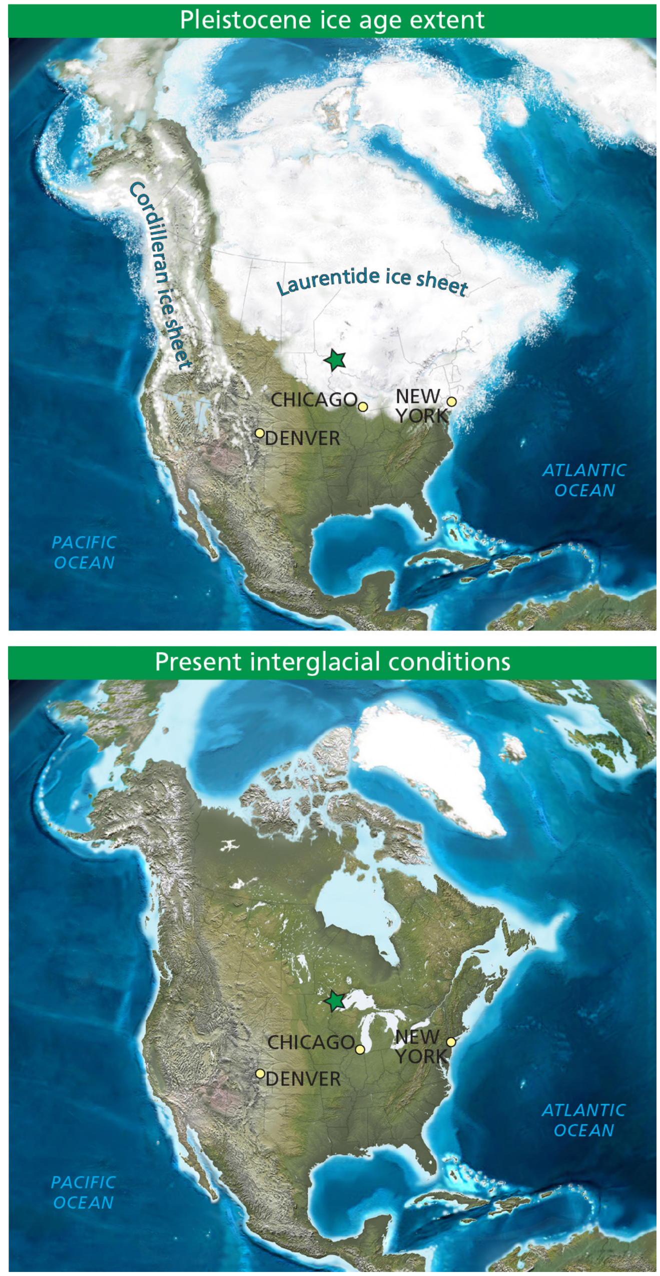


Figure 8. Maps of Ice-age and interglacial conditions.
Nearly half of North America was covered by ice during Pleistocene glaciations. Relative sea level dropped during glaciations (note the expanded width of Florida [white shading]). The location of Grand Portage National Monument is denoted by a green star. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University). Base paleogeographic maps are from "North American Key Time Slices" © 2013 Colorado Plateau Geosystems Inc., used under license.

event, that may have begun about 1.08 billion years ago, reversed the sense of motion along the rift-bounding normal faults, and uplifted the central rift graben relative to its flanks. The rift failed to separate the continent and the landmasses coalesced into a supercontinent called Rodinia, encompassing most of the continental crust in existence at the time. The failed midcontinent rift accumulated thick deposits, collectively called the Keweenaw Supergroup (Thornberry-Ehrlich 2010).

Although the bedrock exposed today at the surface records the ancient geologic history of the area, hundreds of millions of years of Earth history are missing from the surface at Grand Portage National Monument. The intervening geologic record was either not deposited or was weathered away as northern Minnesota was in the middle of the ancient continent or craton of North America for hundreds of millions of years (figs 7 and 4C). During the Pleistocene, more than 10,000 years ago, continental glaciers descended south from Canada (fig. 8) and repeatedly advanced and retreated over the Lake Superior basin (fig. 4D), scouring the basin to bedrock and leaving some glacial deposits. The glaciers eroded the local bedrock with the more resistant diabase (**PCprdb**) standing out as ridges adjacent to the softer Rove Formation (**PCrv**; fig. 9; Miller et al. 2001). When the last glacial lobe—the Superior lobe—retreated from the basin about 10,000 years ago (fig. 4E), the Grand Portage emerged from a succession of pro-glacial lakes which left behind wave-washed sediments, erosional bluffs, and old beaches and bars (Miller et al. 2001; Thornberry-Ehrlich 2010; Rosenthal 2012). Named levels or lake stages of local interest include: Minong, Post-Minong, Nipissing, Algoma, and Sault (Phillips 2003; Birk 2006). Wave action washed against the eastern flanks of Mount Rose during the Nipissing transgression or level rise when the lake was at about 194 m (636 ft) (Phillips 2003; Birk 2006). As lake levels approached their modern elevation, the shoreline has continued to evolve as erosion and wave action rework material. Upland streams meander across their channels, cutting through thick glacial deposits and former lake shoreline terraces (fig. 4F). Changes in lake level also likely impacted the human history of the Grand Portage area; this is an ongoing area of research (William Clayton, Grand Portage National Monument, chief of resources management, written communication 24 June 2019).

Geologic Significance and Connections

Among the monument's significance statements outlined in National Park Service (2017) is the importance of the Grand Portage as a critical transportation route for thousands of years and its role in enabling the fur trade and European expansion into the northwest in the 18th and 19th centuries, as well as the international boundary between the US and Canada. The local geology strongly influenced the development of the landscape and thereby its human history and ecosystems. The sheltered bay on the north shore of Lake Superior with level land, the relatively easy portage around the impassable lower Pigeon River, and the river itself as a natural waterway leading northwestward all factored in to make this site so significant (Woolworth 1993). The erosion-resistant diabase of **PCprdb** underlies the higher ridges of the region such as Mount Rose and Mount Josephine (Miller et al. 2001; Thornberry-Ehrlich 2010). Thompson (1969), Woolworth (1993), White (2005), Phillips (2003), and Bahr Vermeer Haecker Architects/John Milner Associates, Inc. (2009) presented detailed historical and cultural overviews of the monument that are beyond the scope of this GRI report; a short summary highlighting geologic connections is presented here.

Native American Use

Native Americans were the first humans to occupy the portage area after the last glacial retreat of the Pleistocene. Lake Superior evolved through different stages of higher and lower water levels, resulting in old beach ridges and erosional bluffs exposed above the modern lake. Today, Lake Superior is 183 m (602 ft) above sea level. Around 9,500 years ago, the lake level was 218 m (715 ft) during the Lake Minong stage, flooding the lower valley of Grand Portage Creek and creating a deep embayment near its mouth (Phillips 2003; Birk 2006). The peninsula including Mount Rose defined a sheltered bay to the north, which may have attracted Paleo-Indian people (Birk 2006). The portage was used as a trail route from Grand Portage Bay along the shores of Lake Superior to the Pigeon River by Native Americans for thousands of years (Bahr Vermeer Haecker Architects/John Milner Associates, Inc. 2009).

Among the significance statements for the monument is Ojibwe knowledge of and connection to the land, water, plants, and wildlife of the area that allowed them to endure the harsh environment. Other cultures borrowed from the Ojibwe knowledge to exploit the natural resources as global commodities (National Park Service 2017). The French may have learned of the portage route from local Ojibwe in 1722 (Bahr Vermeer Haecker Architects/John Milner Associates, Inc. 2009). Portaging relied upon two critical innovations: the birchbark canoe (light and portable over long distances) and the portage collar, which was a light leather strap used to pack baggage over the portage

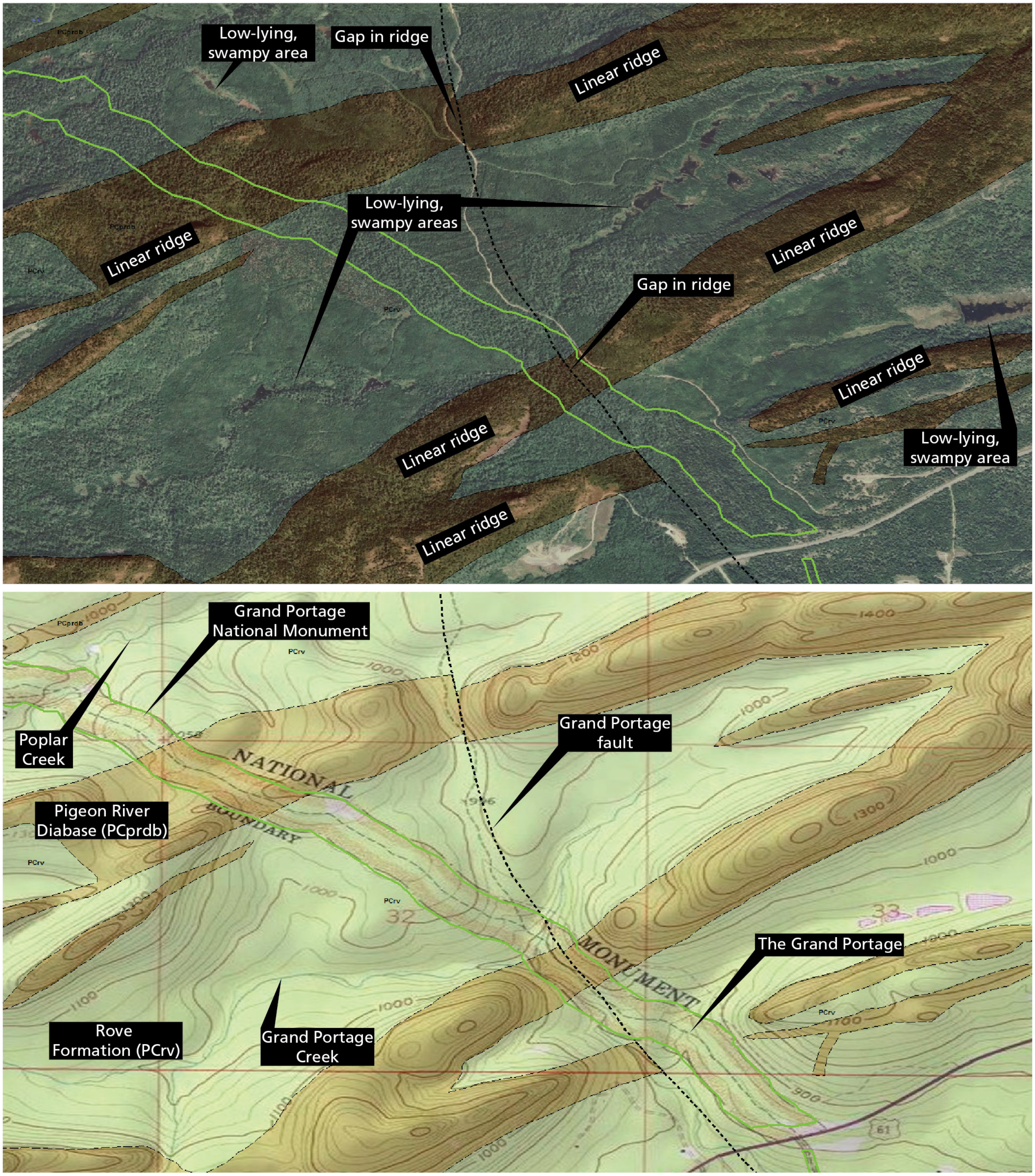


Figure 9. GRI GIS map data draped over aerial imagery and topographic map.
Landform expression at the monument closely correlates with the underlying geologic unit. Low-lying, marshy areas are typically atop Rove Formation (PCrv), whereas the tough, erosion resistant Pigeon River Diabase (PCprdb) supports linear ridges. In places where the ridges were cut by later faulting, gaps weathered through. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using GRI GIS data with a basemap by ESRI World Imagery basemap and USA topo basemaps (both accessed 17 September 2018).

trail. Both innovations were Native American in origin (Woolworth 1993).

Many sites of archeological interest exist within the monument and others are suspected but require excavation; they are a subject of ongoing research (William Clayton, chief of resources management, Grand Portage National Monument, written communication 11 July 2019). Old Copper Culture artifacts, reflecting trade with the groups collecting copper on Isle Royale in northern Michigan, have been found near the southeastern end of the portage (Woolworth 1993; Martin 1999; William Clayton, Grand Portage National Monument, chief of resources management, written communication 11 July 2019). One notable site is where people would shoot arrows to the top of local cliffs (underlain by **PCprdb**) as a game of skill. Cinnabar ore (for mercury-bearing vermilion) factored into trade. Vermilion was used as pigmentation of skin, hair, clothing, and even canoe paddles, and was highly prized by Native American populations. Mercurials, including elemental mercury and ionic mercury often mixed with fats, were frequently used by traders for medicinal purposes (Rolfhus and Seitz 2017). The archeology of the trail corridor remains as a survey need and exact dates of early human use remain elusive (Birk 2006; National Park Service 2017).

The Portage

The Grand Portage corridor or Gitchi Onigaming (Great Carrying Place) is a fundamental resource and value at the monument of cultural, historical, archeological, geological, and recreational significance (National Park Service 2017). According to Woolworth (1993), portage trails document the ages-old relationship between humans and their environment; it is a trail or carrying place between two water bodies. The landscape of the Grand Portage allowed passage or portage of valuable furs and supplies for trade around a series of treacherous rapids underlain by hard, diabase dikes (analogous to **PCprdb**) on the course of the Pigeon River, too difficult to navigate with the canoes and other watercraft in use at that time. The Pigeon River was the access waterway to the northwest between Lake Superior and Fort Charlotte. Pigeon Falls occurs where the river cuts through a 27-m- (90-ft-) high ridge of diabase. The 13.7-km- (8.5-mi-) long Grand Portage and its annual August rendezvous may have been the single most important fur-trade location in North America for the trade between Montreal and the northwestern area of the continent; only Hudson Bay surpassed the Grand Portage as a natural route in the heart of northern North America during the nearly 200 years of the fur trade (Woolworth 1993; Miller et al. 2001; Thornberry-Ehrlich 2010).

The route of the Grand Portage is greatly influenced by the topographic character of the land over which it passes. The trail uses the Grand Portage Creek valley, the gap in the diabase ridge, the higher ground (interfluves) of the Poplar Creek basin (except where it must cross the creeks), and, above Old Hwy 61, the diabase ridges (except where it crosses the Beaver Meadow; Phillips 2003). The present trail is unlikely to represent the historic trail at all points along its length; there were alternative trails depending on the mode of transport (i.e., on foot or using carts) and seasonal conditions. Rest areas undoubtedly existed along its length as well, possible locations being terrace surfaces, summits of interfluves, and any non-boggy valley floors (Phillips 2003).

The ridges created by alternating bands of resistant diabase between valleys of softer argillite (**PCrv**) made the portage a hiking challenge to a porter hauling two 82-kg (180-lb) packs each way. The portage rises nearly 219 m (718 ft) above Lake Superior along its course (Woolworth 1993; Phillips 2003). The trail was often slippery with wet clay areas and tree roots. The clay-filled, commonly marshy or boggy valleys are due to glacial deposits of till and glacial lake clays that accumulated on top of the Rove Formation (**PCrv**) and today harbor wetlands (Miller et al. 2001; Kraft et al. 2014). The southern portion of the portage follows the trace of the Grand Portage fault (unnamed in the GRI GIS data), which may have provided a zone of weakness for preferential weathering and erosion forming a natural passage or gap (see “Faults”; Thornberry-Ehrlich 2010).

Sources of water were a concern along the higher reaches of the portage beyond Grand Portage Creek and Poplar Creek. Much of this upper section crossed terrain of bare rock or thin, sandy glacial sediments with little opportunity for water flow (Phillips 2003). Excavated pits (e.g., “the fountain”) collected runoff and rainwater and enhanced catchments below seeps emerging from fractured bedrock (e.g., “the springs”) would provide an almost perennial source of water (Phillips 2003).

Aside from the interpreted cultural features at the monument, historians suggest there may be unexcavated remains of other forts or outposts (possibly from the American Fur Company, or the XY Fort) on park land on the eastern or southwestern side of the monument or also on the Ojibwe Indian Reservation (Thornberry-Ehrlich 2010).

As mentioned in “Native American Use,” different lake levels are associated with different archeological periods. In 1768, John Askin arrived at Grand Portage and began to clear a large area near the site of what would eventually become a large headquarters (Bahr Vermeer Haecker Architects/John Milner Associates, Inc. 2009). The trading post north of Mount Rose is on a Post-Minong surface at about 206 m (675 ft) elevation. The Grand Portage Band headquarters and school, the log-school, and catholic church are on a Post-Minong surface above 201 m (660 ft). The Grand Portage National Monument canoe warehouse is near the elevation of the Algoma stage at 189 m (621 ft), and the Great Halls is on a gentle bluff of the Sault stage when the lake was at 186 m (610 ft) close to the modern level (Phillips 2003; Birk 2006).

Ecosystem Connections

Following the retreat of the last Pleistocene glaciers about 12,000 years ago, the heavily glaciated landscape consisted of scoured high areas and filled in low areas (Kraft et al. 2014). Topography was uneven with gravel hills and ridges, swamps, and rock outcrops (Woolworth 1993). Today, forest and woodlands cover over 92% of the monument (Kraft et al. 2014). The park is part of the "North Shore Highlands" and "Boundary Lakes and Hills" ecoregions as defined by the US Environmental Protection Agency (USEPA). North Shore Highlands are hills above Lake Superior with many streams draining into the lake, whereas Boundary Lakes and Hills are forested hills with thin soils and irregular slopes interspersed with many lakes (USEPA 2010; Kraft et al. 2014). The mid-continental climate with hot summers and cold winters is greatly tempered by its location on Lake Superior. The lake causes more moderate temperatures, increased precipitation, and slightly later summers. The further away from the lake, the climate is drier and more prone to temperature extremes (Kraft et al. 2014).

Geology interacting with time, climate, biology, and landforms, gives rise to habitat-supporting soils. Soil resources are the subject of the NPS Soil Resources Inventory (SRI; see https://www.nps.gov/subjects/geology/sri.htm), but in general the local soils range from alluvial, stony/bedrock, clays, and loams (Gafvert 2009a; Kraft et al. 2014). Soil formation starts once the land surface is stable. Soil development occurs much more slowly on the exposed igneous bedrock (**PCprdb**) compared to the glacial sediment-filled interridge areas (Miller et al. 2001; Gafvert 2009a). Poor local soils and the short summers also impacted the local trade history, given food was in such short supply (White 2005).

Habitats with clear ties to geology in the monument include cobble beaches, steep and open talus slopes (Mount Rose), floodplain forests, wetlands, rocky outcrops, and dry moderate slopes (Kraft et al. 2014). Shallow and sheltered Grand Portage Bay is a prominent feature in the history and ecosystem of the monument. Raised beach material varying in grain size from fine sand to cobbles compose the present shoreline (Phillips 2001; Kraft et al. 2014). Most of the bay, landward of Grand Portage Island, is shallow, less than 4 m (13 ft) deep (Kraft et al. 2014). For monument streams such as Grand Portage Creek, water flow patterns and the interplay of water, riverbed, and riparian areas influences the natural diversity of habitats and species (Kraft et al. 2014). Sediment transport patterns are critical to the support of underwater, riparian, and wetland habitats (Kraft et al. 2014). Wetlands are transitional areas between land and water bodies, where water periodically floods the land or saturates the soil and includes marshes, swamps, seeps, pools, and bogs. Wetlands in the monument are commonly underlain by Rove Formation (**PCrv**) and impermeable, clay-rich glacial deposits (Miller et al. 2001; Kraft et al. 2014). They may be covered in shallow water most of the year or be wet only seasonally. Wetlands provide several significant functions, including (1) provision of bird and other wildlife habitat, (2) surface water detention, (3) nutrient transformation, and (4) retention of sediments. The monument's abundant streams and marshy areas support myriad flora and fauna. One Minnesota endangered plant, four threatened plants, and 11 plant species of special concern grow locally. Three Minnesota threatened fauna and four fauna of special concern live within monument boundaries. Within the monument, Snow Creek supports a vigorous beaver colony—beaver being a critical element in the area's fur-trade history (Kraft et al. 2014). Other species of interest dependent on this landscape of alternating ridges and marshes include moose, gray wolf, and coaster brook trout (native to Lake Superior; Kraft et al. 2014). According to the monument's natural resources condition assessment (Kraft et al. 2014), stream aquatic habitats, land cover, and inland waters are of good or stable condition.

Predicted climate change trends will impact the shoreline, streams, and ecosystem at Grand Portage National Monument. Climate models indicate that summer temperature is projected to increase by 2.6°C (4.7°F) by 2040 (data are for nearby Isle Royale) and storms will increase in frequency and severity by 50–100% (Kling et al. 2003; Davey et al. 2007; Saunders et al. 2011; Kraft et al. 2014; Monahan and Fisichelli 2014; National Park Service 2017). Visitation at Grand Portage National Monument is strongly tied to temperature; visitation is predicted to increase as much as 108% with warming temperatures placing increasing demands on the monument ecosystem and infrastructure (Fisichelli and Ziesler 2015). The National Oceanic and Atmospheric Administration (NOAA) has been tracking climate fluctuations since the 1950s. The Great Lakes region has experienced above average temperature increases during that period of time. Climate change impacts and responses for scenario planning is among the planning and data needs (medium priority) identified in the monument's foundation document (National Park Service 2017).

Additional information about other natural resources is available in the following references.

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- Species lists at NPSpecies website: https://irma.nps.gov/DataStore/Reference/Profile/2205731 (accessed 9 September 2019).
- Biotic stressors: Fisichelli, N. A., S. R. Abella, M. P. Peters, and F. J. Krist Jr. 2014. Climate, trees, pests, and weeds: change, uncertainty, and biotic stressors in eastern U.S. national park forests. Forest Ecology and Management 327:31–39. https://irma.nps.gov/DataStore/Reference/Profile/2219245 (accessed 9 September 2019).
- Information regarding the monument's water resources is available from the NPS Water Resources Division (http://go.nps.gov/waterresources)
- Groundwater report: Paillet, F. L., and J. D. Olson. Analysis of the results of hydraulic-fracture stimulation of two crystalline boreholes, Grand Portage, Minnesota. Water-Resources Investigations Report 94-4044. US Geological Survey, Reston, Virginia. https://doi.org/10.3133/wri944044 (accessed 9 September 2019).
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- The NPS Great Lakes Network currently inventories and monitors natural resources such as climate, amphibians, diatoms, inland lake water quality, landbirds, land cover and land use, large river water quality, persistent contaminants, and vegetation (https://www.nps.gov/im/glkn/index.htm).
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- Landscape history and historical observations, including lake-level effects on early human habitation: Phillips, B. A. M. 2003. Geomorphological and historical observations in the Grand Portage National Monument. Unpublished report prepared for the National Park Service, Grand Portage National Monument, Grand Marais, Minnesota. Lakehead University, Thunder Bay, Ontario, Canada.
- Archeological surveys: Birk, D. A. 2006. Grand Portage National Monument maintenance area preliminary survey report. Unpublished report on file with Grand Portage National Monument, Grand Marais, Minnesota. https://irma.nps.gov/DataStore/Reference/Profile/2197350. (accessed 14 April 2018).

Geologic Features, Processes, and Resource Management Issues

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

During the 2010 scoping meeting (see Thornberry-Ehrlich 2010) and 2018 conference call, participants (see Appendix A) identified the following features, processes, and resource management issues: shoreline erosion; fluvial features and processes; geologic hazards; disturbed lands; potential mineral and energy development; glacial features and lake stages; faults; ancient bedrock; and paleontological resource inventory, monitoring, and protection. Each is discussed when possible with regard to the relevant geologic map units (table 2).

Shoreline Erosion

About 400 m (1,300 ft) of Lake Superior shoreline is part of the monument and the lake is identified as a resource in the monument's foundation document (National Park Service 2017). Interactions between longshore lake currents, wave action, sediment supply, and incoming streams control erosional and depositional areas along the lakeshore (Thornberry-Ehrlich 2010). Differential isostatic tilting (rebound from the absence of continental glaciers' weight) and the infrequent incidence of storms and storm-related water-level rises from the southeast and east are the most likely causes of chronic shoreline erosion (Phillips 2001; Kraft et al. 2014). According to the monument's natural resources condition assessment (Kraft et al. 2014), the geomorphology of Grand Portage Bay is in a stable trend and good condition.

Prior to 1910, a large delta protruded into Lake Superior at the mouth of Grand Portage Creek. Then, a road construction project altered the system and changed the delta configuration. Scraped fill covered up to one-third of the former delta's area and resulted in shoreline changes which obscured or destroyed historic features such as Premiers Point. This feature was part of 1790s accounts of the area, forming from the interaction between longshore currents and creek flow to create a cobble spit area projecting into the lake (Thornberry-Ehrlich 2010).

Fluvial Features and Processes

Fluvial features are those which are formed by flowing water. Fluvial processes both construct (deposit alluvial sediments) and erode landforms (e.g., valleys or gullies). Fluvial features occur on many scales in the monument ranging from the large creek valleys to small tributary valleys to the smallest streams. Examples of the park's fluvial features include channels, point bars, floodplains, and terraces (fig. 10). Grand Portage Creek empties into Lake Superior within monument boundaries. Approximately 1 km (0.6 mi) of the creek

Table 2. Description of geologic map units mapped in Grand Portage National Monument.

Map Unit (symbol)	Physical Description and Occurrence in Grand Portage National Monument
Pigeon River diabase (PCprdb)	The monument boundary cuts across alternating bands of **PCrv** and **PCprdb**. **PCprdb** occurs in bands of northeast- and northwest-trending dikes that cut the original texture of **PCrv**. Diabase is an intrusive igneous rock composed dominantly of plagioclase, augite, olivine, and Fe-Ti oxide minerals such as magnetite and ilmenite. Fresh (unweathered) outcrop exposures appear dark gray to black. The portage crosses **PCprdb** five times along its length. Rocks from PCprdb were used in the construction of the CCC-era Stone Bridge and other infrastructure as an accent stone.
Rove Formation (PCrv)	The monument boundary cuts across alternating bands of **PCrv** and **PCprdb**. **PCrv** underlies more than 70% of the total monument area and consists of thin-bedded argillite—which is slightly metamorphosed fine-grained mudstone or shale. Some portions of the Rove Formation include areas that are richer in quartz (quartzite) and some bands that were exposed to greater heat/pressure during metamorphism becoming mica-rich schists. Rocks from **PCrv** were used in the construction of the CCC-era Stone Bridge and other infrastructure. It was the primary building material. Low-lying areas of **PCrv** underlie wetlands and marshes in the monument separated by ridges of **PCprdb**.

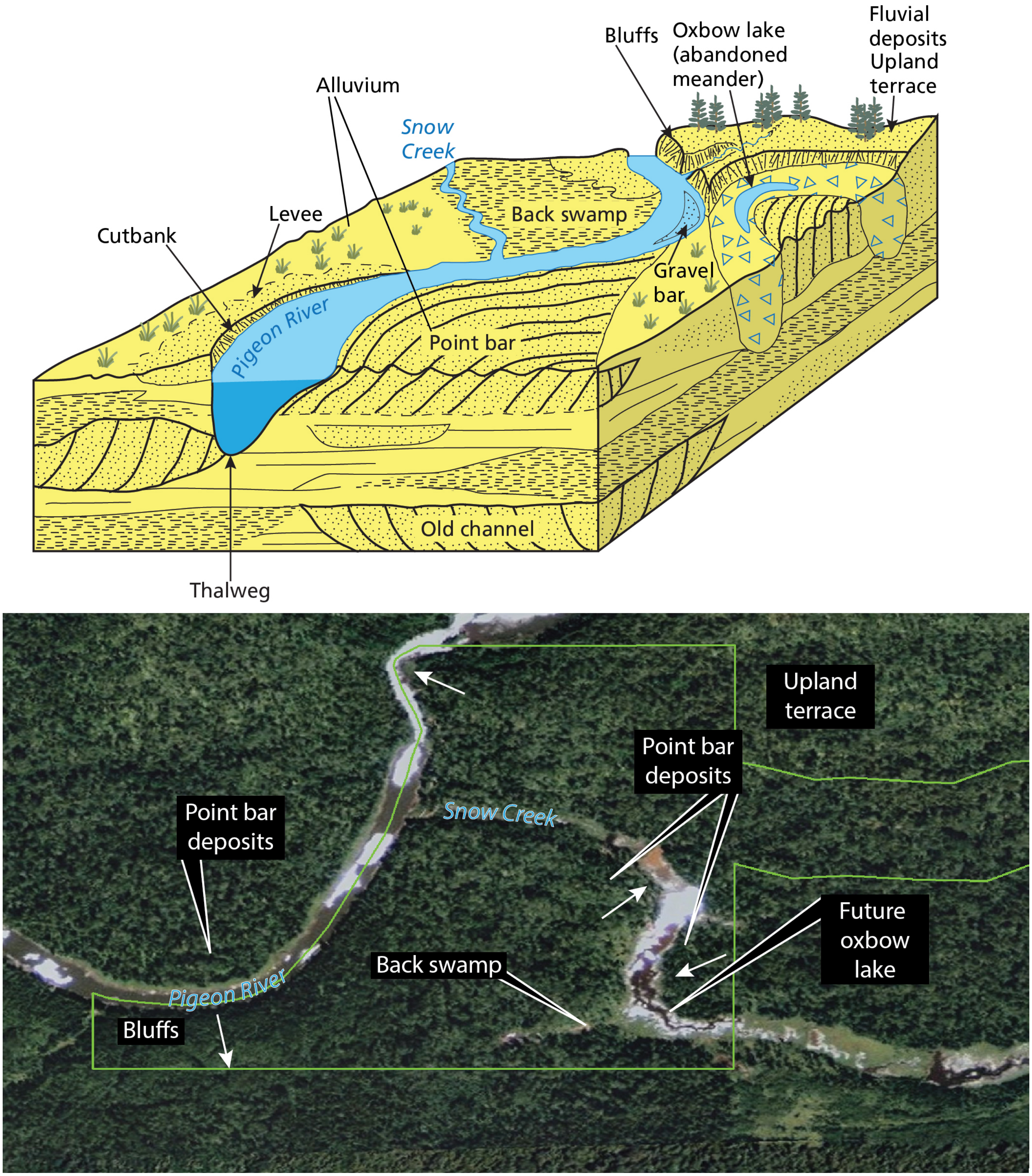

Figure 10. Schematic illustration of fluvial deposits and depositional settings.
Several of the monument's streams are flanked by swamps and wetlands. The rivers and streams incise an upland area. White arrows indicate the directon of river meander. Graphic by Trista Thornberry-Ehrlich (Colorado State University) using GRI GIS data with a basemap by ESRI World Imagery basemap (accessed 17 September 2018).

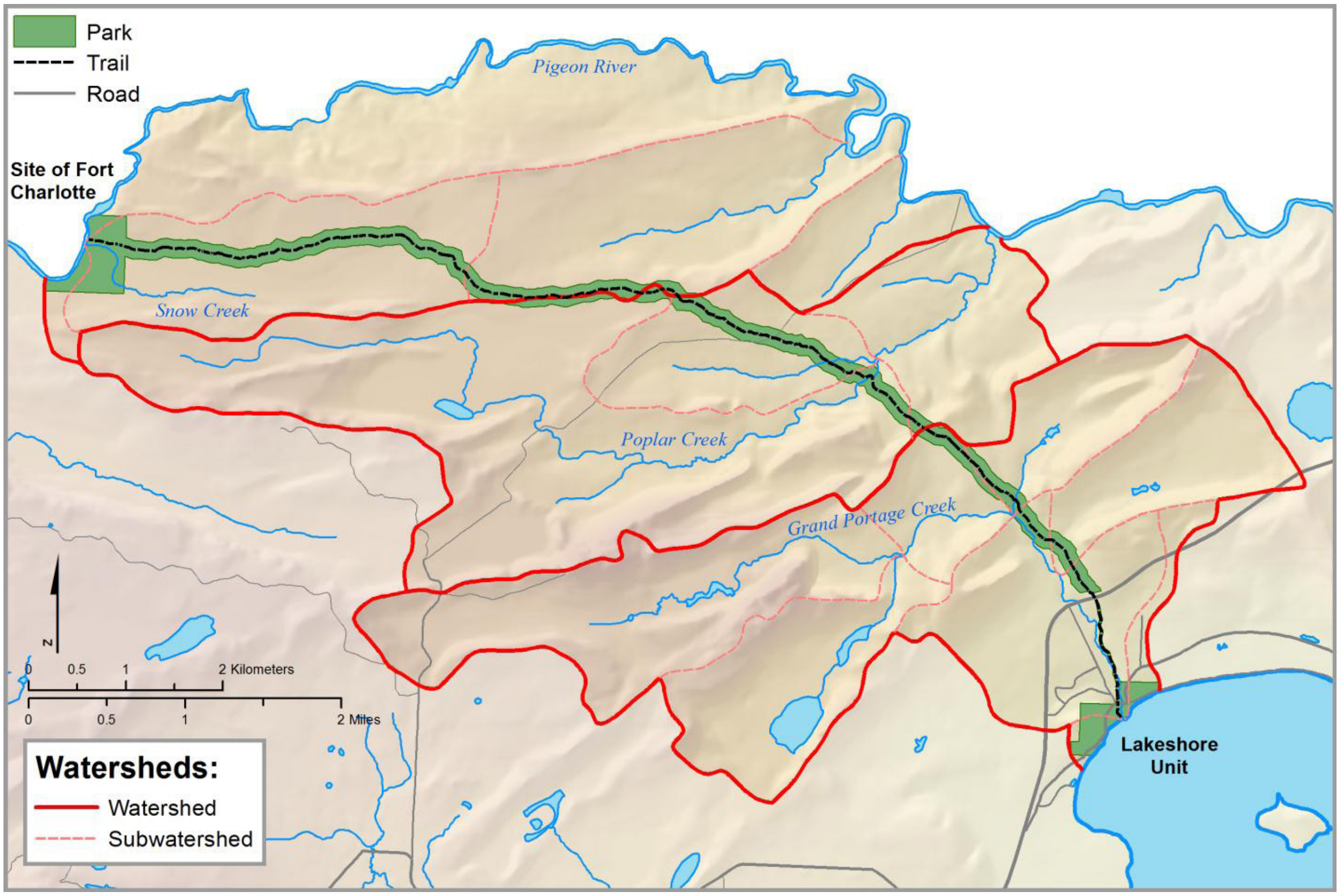

Figure 11. Map showing watersheds and subwatersheds within Grand Portage National Monument. The monument is entirely within the northwestern Lake Superior watershed, in the Baptism-Brule subwatershed. Within the Baptism-Brule, three subwatersheds intersect the monument boundaries: Upper Pigeon River (Snow Creek), Poplar Creek, and Grand Portage Creek. Graphic is figure 9 from Kraft et al. (2014).

is within monument boundaries and it is identified as significant to both the natural and cultural resources of the monument (Kraft et al. 2014). Grand Portage Creek, Poplar Creek, Snow Creek, and several smaller, unnamed streams form the fluvial features at Grand Portage National Monument (fig. 11; Phillips 2003). Channels are the perennial course of the flowing water. As a creek flows around curves the flow velocity (and thus erosive energy) is greatest on the outside of the bend. The creek erodes into its bank on the outside of a curve and leaves point bar deposits on the inside of the bend. Point bars are crescent-shaped ridges of sand, silt, and clay deposited on the inside of meander loops where the water's velocity is slowest. As the process continues, the outside bend retreats farther, while the inside bend migrates laterally, thus creating migrating meanders. Some of the monument's creeks are primarily flowing through entrenched meanders, incised directly into bedrock (e.g., Pigeon River). Their lateral migration is slow compared to classic meandering streams through unconsolidated surficial deposits (fig. 12). Poplar Creek passes through clearcut areas and has a resulting higher than normal sediment load (Thornberry-Ehrlich 2010). Some areas of the Grand Portage trail are boardwalked to prevent further erosion (National Park Service 2017).

Geologic Hazards: Slope Movements and Earthquakes

A geologic hazard ("geohazard") is a natural or human-caused geologic condition or process that may impact park resources, infrastructure, or visitor safety. Risk is the probability of a hazard to occur combined with the expected degree of damage or loss that may result from exposure to a hazard, or the likelihood of a hazard causing losses (see Holmes et al. 2013). Slope movements, also called "mass movements" or referred to generally as "landslides," have occurred and will continue to occur in the monument. Slope movements are the downslope transfer of material (e.g., soil, regolith, and/or rock) (fig. 13). Slope movements can

Figure 12. Photograph of a meandering section of Grand Portage Creek.
Riprap was installed prior to 2005 in an attempt to stabilize the bank and prevent loss of cultural resources. View is to the east, just below the old ford, upstream of the stone bridge. Annotated graphic is figure 12 in Birk (2006).

occur very rapidly (e.g., debris flows or rockfall) or over long periods of time (e.g., slope creep). The magnitude of slope failures depends on slope, aspect, soil type, and geology. Slope movements are natural processes; they become hazards when visitors hike near the base of cliffs or under rock overhangs. Particularly hazardous areas are those with visible cracks, loose material, or overhangs (fig. 14). They also become hazards when they undermine or impact infrastructure (e.g., trails, roads, parking lots, other facilities) or already disturbed lands. Slope movements can also damage or destroy other natural or cultural resources. There are many natural factors that contribute to slope movement. Frost weathering, plant-root wedging, streambank erosion, and differential erosion cause slope instability. Areas with denuded or disturbed vegetation are susceptible to increased erosion which can reduce slope stability.

In the monument, the Mount Rose area has rocks and talus deposits susceptible to movement. Much of the observed movement is related to visitor use (e.g., scrambling; Grand Portage National Monument staff, conference call, 31 October 2018). In places where the Pigeon River diabase (geologic map unit **PCprdb**) underlies ridges or hilltops that compose steep slopes, blockfall is a potential hazard. Muddy, weathered areas of the Rove Formation (**PCrv**) may pose a falling hazard along the portage trail.

Seismic activity (earthquakes) are ground vibrations that occur when rocks suddenly move along a fault, releasing accumulated energy. Earthquake intensity ranges from imperceptible by humans to total destruction of developed areas and alteration of the landscape. Situated in the ancient cratonic core of North America, Grand Portage National Monument has a relatively low risk for seismic hazards (fig. 15).

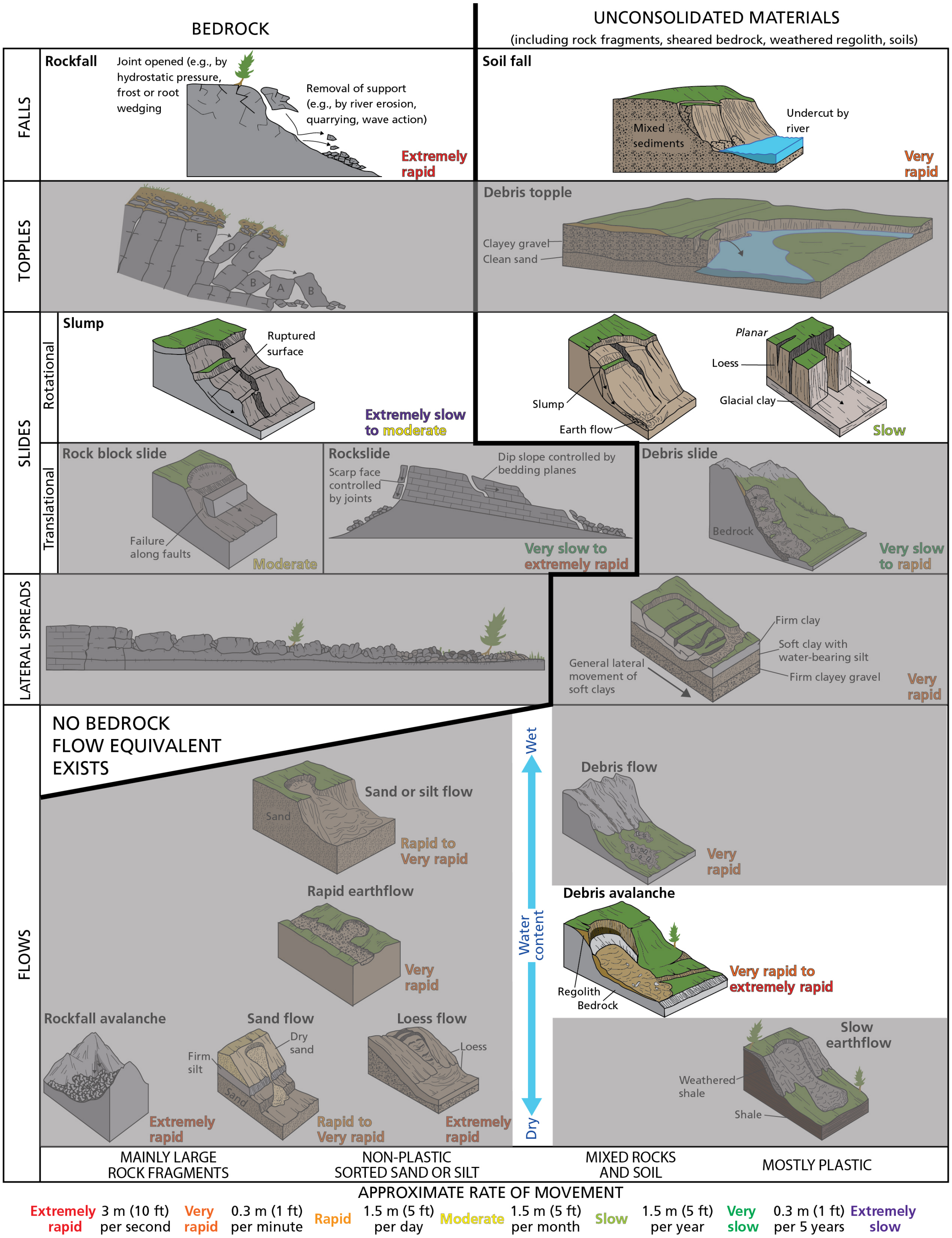

Figure 13. Schematic illustrations of slope movements.
Different categories of slope movement are defined by material type, nature of the movement, rate of movement, and moisture content. Gray-shaded areas depict slope movements that are not likely to occur in Grand Portage National Monument. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Varnes (1978, figure 4.33 and information therein).

Figure 14. Annotated photograph of cliffs and slope deposits.
This particular outcrop shows a steep slope in the Rove Formation (PCrv). The weathered metasedimentary rocks are layered and fractured. Blocks of this formation are spalling off the face of the cliff, forming slope deposits (talus) below. NPS photograph, annotation by Trista L. Thornberry-Ehrlich (Colorado State University).

Regionally, seismic events occur as buried, ancient faults accommodate stresses within Earth's crust, particularly those associated with isostatic rebound in the Great Lakes area. Isostatic rebound is the upward movement of land adjusting to the removal of the weight of the continental ice sheets that buried the area over 10,000 years ago. Even moderate earthquakes can directly damage park infrastructure or trigger other hazards such as liquefaction (the transformation of a solid soil to a liquid) or slope movements that may impact park resources, infrastructure, or visitor safety. Park staff are unaware of any recorded earthquakes felt by humans at the monument (William Clayton, Grand Portage National Monument, chief of resources management, written communication 24 June 2019).

Disturbed Lands

Disturbed lands are where natural conditions and processes have been directly impacted by development, including facilities, roads, dams, landfills, and abandoned campgrounds; agricultural activities such as farming, grazing, timber harvest, and abandoned irrigation ditches; overuse; or inappropriate use. Logging and grazing preceded the creation of the monument, dating back to the 1700s and 1800s (Thornberry-Ehrlich 2010). The removal of stabilizing vegetation and overuse by animals probably contributed to increased erosion, particularly near streams. Mount Rose (an important resource and value; National Park Service 2017) was once completely bare of forest as logging occurred in two phases: one for homestead settlement, and one for commercial logging. Usually, lands disturbed by natural phenomena such as landslides, earthquakes, floods, and fires are not

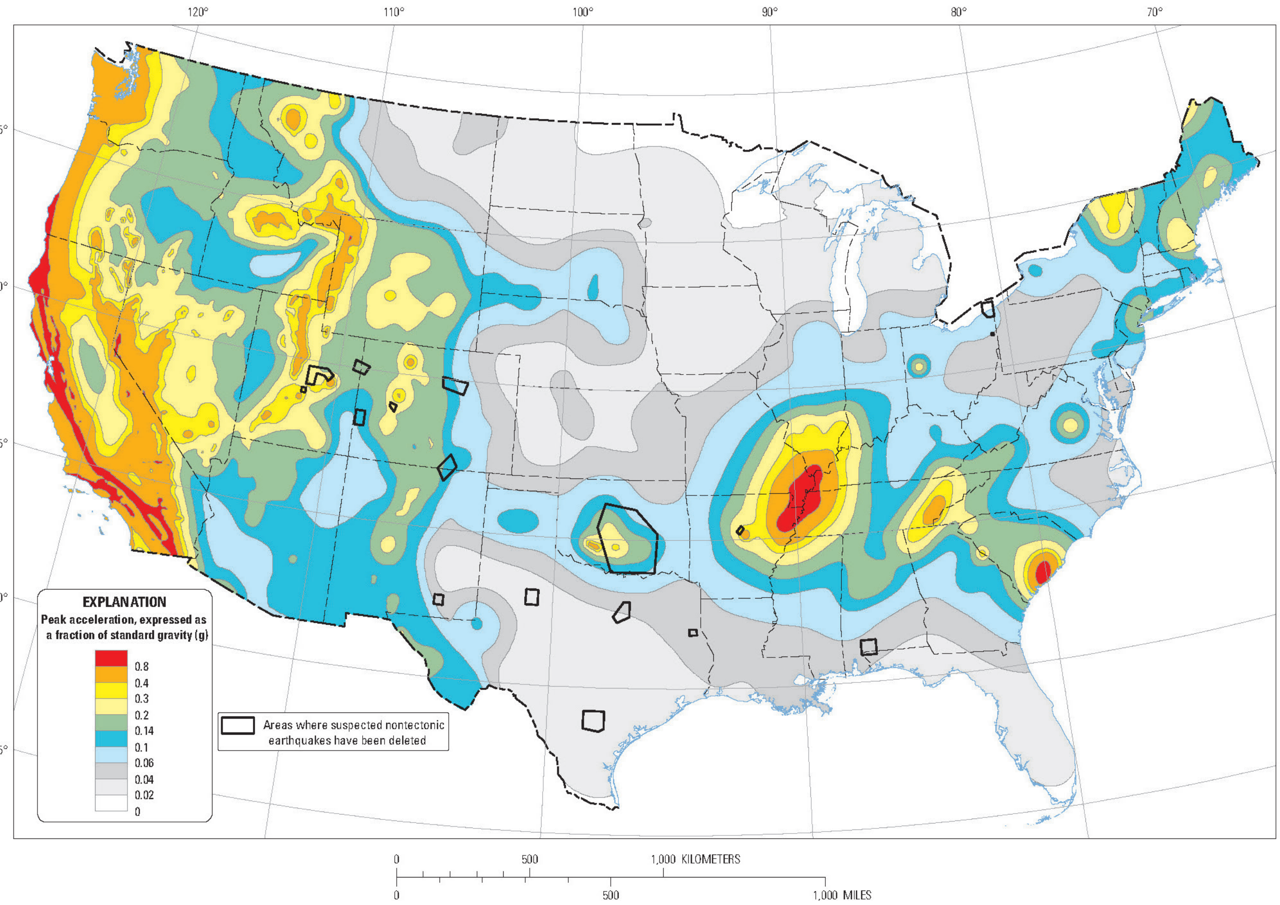

Figure 15. Seismic hazards map for the lower 48 states.
Legend depicts the probability of a strong earthquake within the next hundred years with warmer colors denoting areas of higher risk. Northern Minnesota is considered at very low risk for an earthquake. Graphic courtesy of the US Geological Survey; available at https://earthquake.usgs.gov/static/lfs/nshm/conterminous/2014/2014pga2pct.pdf.

considered for restoration unless influenced by human activities. Restoration activities return a site, watershed, or landscape to some previous condition, commonly some desirable historic baseline. Because of its long human history, most if not all anthropogenic features including the portage itself, while disturbed, are part of the cultural interpretive story at Grand Portage National Monument (Thornberry-Ehrlich 2010). An exception to this rule is the high concentration of mercury in soils associated with the forts at either end of the portage. The monument is letting most of the 1900s-era landscapes naturally revegetate to a forest environment, consistent with a cultural landscape report (Thornberry-Ehrlich 2010; Brandon Seitz, Grand Portage National Monument, resource assistant, written communication 24 June 2019).

Potential Energy and Mineral Development

Lead and zinc ores are part of the local bedrock. No mines exist inside the monument boundary and mining would not be allowed there, but energy and mineral development could proceed in surrounding areas and negatively impact monument resources. As of 2010, several companies were exploring the region for copper, nickel, and platinum group elements (PGEs) that occur in the gabbroic rocks of the Duluth Complex, west of the Grand Portage; similar-age rocks are being explored north of the monument in Canada with further exploration expected, but not locally (Thornberry-Ehrlich 2010; Terry Boerboom, geologist, Minnesota Geological Survey, conference call, 31 October 2018).

Local discussions are ongoing about the potential for wind farm development on ridgetops in the monument area and along the shores of Lake Superior. If close enough, these would impact monument viewsheds.

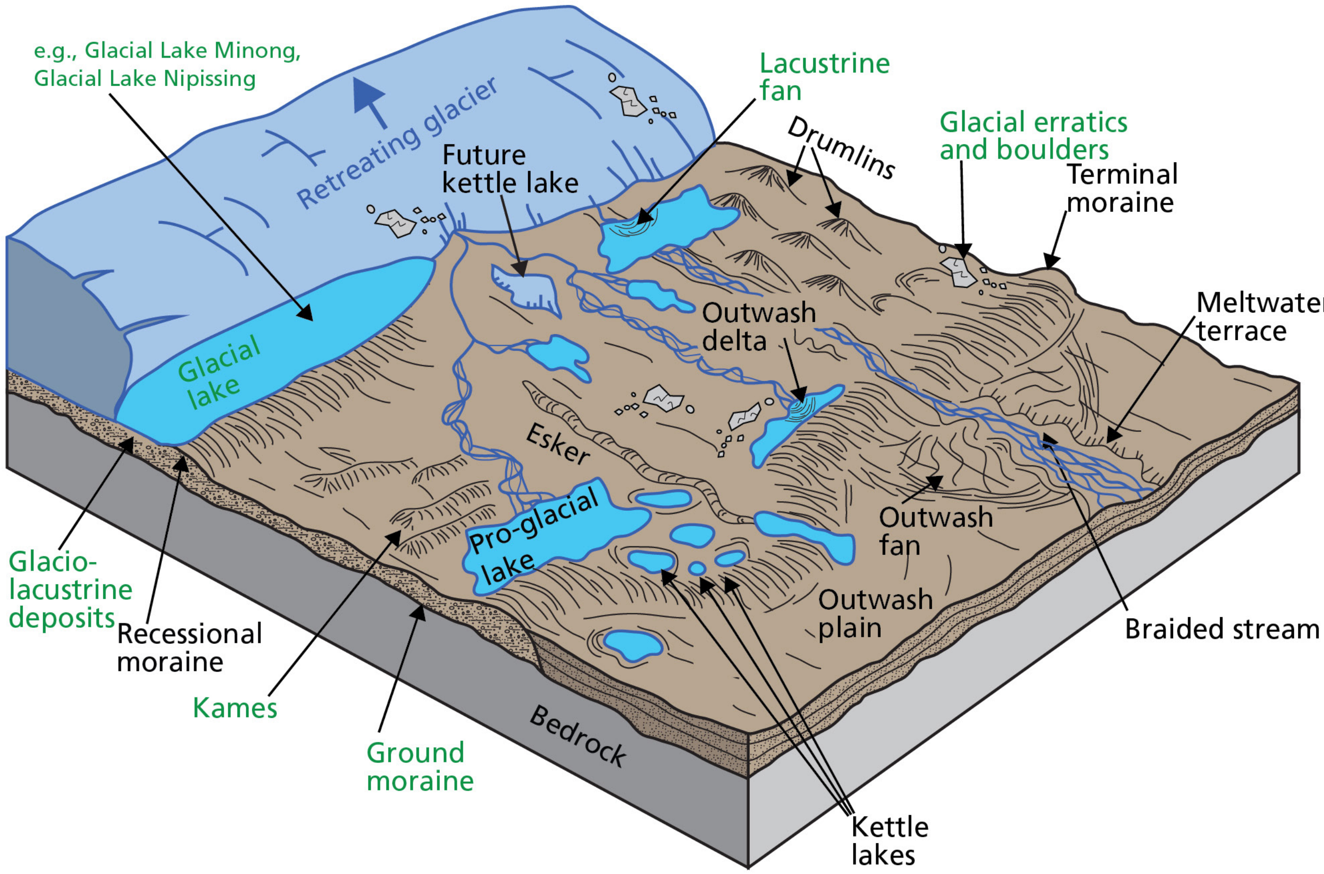

Figure 16. Schematic illustration of glacial features and deposits. Glacial features that are likely to occur within Grand Portage National Monument are labeled in green with local examples indicated. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

Transmission lines from wind farms would not be allowed to cross the Grand Portage trace (Thornberry-Ehrlich 2010).

Glacial Features and Lake Stages

Pleistocene glaciers scoured and reshaped the landscape of the northeastern United States, including Grand Portage National Monument. The most recent ice age (called the "Wisconsinan") completely covered northern Minnesota with ice. It overprinted other major advances; the second most recent was called the "Illinoian." In the monument area, the Rainy lobe (and St. Louis sublobe) descended south from Canada in the west and the Superior lobe excavated the Lake Superior basin in the east. Glacial lobes descending into the Great Lakes area became progressively thinner with distance southward (Thornberry-Ehrlich 2010).

The two major categories of glacial features are (1) those created by glacial ice and (2) those deposited by rivers flowing beneath or out of glaciers, referred to as "glaciofluvial," or deposited in lakes near glaciers, referred to as "glaciolacustrine." Masses of flowing glacial ice change the landscape via plucking (pulling up and entraining rocks from the surface), abrasion (leaving glacial grooves and striations), and the high-pressure flow of sub-glacial meltwater, which can flow unaffected by gravity leaving seemingly enigmatic upslope flowing "stream" deposits or steep-sided tunnel valleys (Phillips 2003). The glaciers carried vast amounts of sediment that were dumped as the ice melted; the majority of the glacial deposits fall into four main categories (fig. 16) till, lacustrine, outwash, and ice-contact sand and gravel. The glacial sediments were then reworked by streams and lakes that formed as the ice melted. The sediment-rich system left sorted channel, floodplain, and delta deposits across the area among mantles of glacial till and small bedrock outcrops. Because the initial bedrock surface was not level, depth of glacial sediments varies from virtually none (bare bedrock exposure), to 10s of meters (100s of feet) (Terry Boerboom, geologist, Minnesota Geological Survey, conference call, 31 October 2018).

A series of proglacial lakes partially filled the Lake Superior basin—forming landward of large, retreating continental glaciers at various times throughout the

Pleistocene (table 1) Among these were Glacial Lake Duluth, which collected vast amounts of clay-rich, lacustrine deposits in low-lying areas between diabase dike (geologic map unit **PCprdb**) islands (Miller et al. 2001). As discussed in “Geologic Significance and Connections,” a series of lake stages left distinctive shoreline features analogous to a staircase across the area and likely influenced early human history there (Phillips 2003). Shoreline areas of these lakes are left as perched terraces (lake levels Algoma and Sault) and beach ridges within the monument (Birk 2006; Rosenthal 2012). The GRI GIS data include former, post-glacial lake levels for glacial lakes Houghton, Superior, Sault, Algoma, Nipissing, and Minong with their respective elevations (Rosenthal 2012). The beach ridge deposits range in grainsize from boulders and gravel to fine sands and impermeable clays (Birk 2006). Distinctive red clay and loamy sediment cap these terraces (Thornberry-Ehrlich 2010).

Glacial erratics, or foreign chunks of rock, ice-rafted and dropped on the landscape also occur in the monument area. Geologists have traced erratics to the Hudson Bay area, some of which may be fossiliferous Ordovician and Silurian rocks (see “Paleontological resource inventory, monitoring, and protection”; Thornberry-Ehrlich 2010).

Another process associated with continental glaciation and perhaps still affecting the monument today, is isostatic rebound or the rise of land masses that were once depressed by the huge weight of glacial ice sheets. The amount of local rebound is still a subject of scientific debate, but investigators agree that after the glaciers receded, the land surface began to uplift without the weight of glacial ice pressing it down. In the Great Lakes, isostatic rebound is linked to rises in lake level (Thompson 1998). Glacial ice was thicker in the Lake Superior basin and retreated later than other lobes (e.g., Lake Michigan). Glacial rebound has been greater in Lake Superior and this resulted in tilted beaches dipping toward the west (Thornberry-Ehrlich 2010). The heavier the ice in any particular location, the greater the rebound; uplift at the Pigeon River is about 76 m (250 ft) greater than at Duluth, Minnesota (Phillips 2003). Streams flowing during isostatic uplift and falling lake-water levels have resulted in the lengthening of stream courses and the deep incision of their beds as they flow to meet the lakeshore at grade (see “Fluvial Features and Processes”; Phillips 2003). Consequently, the north shore abounds in gorges, waterfalls, and rapids as outcrops of more resistant rock (diabase **PCprdb**) inhibit equal incision at all points along the stream course (Phillips 2003). Another characteristic feature is the building of deltas at successively lower elevations as the stream course extends, each in part constructed from the material eroded from an earlier

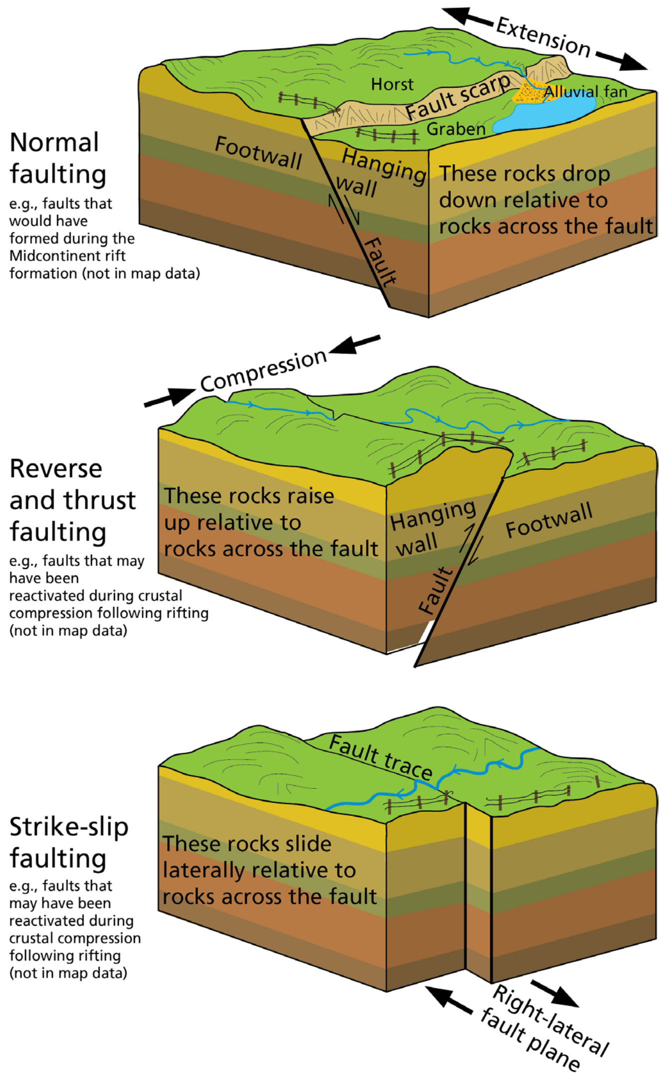

Figure 17. Schematic illustrations of fault types. Movement occurs along a fault plane. Footwalls are below the fault plane and hanging walls are above. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging wall up relative to the footwall. A thrust fault is similar to a reverse fault, but has a dip angle of less than 45°. In a strike-slip fault, the relative direction of movement of the opposing plate is lateral. When movement across the fault is to the right, it is a right-lateral (dextral) fault, as illustrated above. When movement is to the left, it is a left-lateral (sinistral) fault. A strike-slip fault between two plate boundaries is called a transform fault. The Grand Portage fault is not labeled in the GRI GIS data, which includes fault traces of unknown offset/displacement. The Pigeon Point data include left-lateral and right-later strike slip faults beyond monument boundaries. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Figure 18. Photograph of the weathered gap through which the Grand Portage trail crosses. The trace of a fault may be the reason for the localized weathering of a diabase (PCprdb) ridge. The fracturing associated with faulting may have created a weakness in the bedrock. The gap is about 2 km (1 mi) inland from the lakeshore (Birk 2006). Photograph is an NPS image presented as figure 4 in Kraft et al. (2014).

delta because of incision into the former delta surface. An abandoned deltaic fan is perched high above the modern lake level in the Grand Portage River corridor between Grand Portage Bay and Highway 61, which is likely associated with a stream entering a higher glacial lake (Phillips 2003; Thornberry-Ehrlich 2010).

Faults

A fault is a fracture in rock along which movement has occurred. Faults are defined by the direction of movement along the fracture as either normal faults, reverse faults, or strike-slip faults (fig. 17). Strike-slip faults and faults of unknown offset/displacement are part of the GRI GIS map data for the monument. Grand Portage lends its name to a local fault (unnamed in the GRI GIS map data), which likely focused some weathering to form a natural gap or notch (figs. 18 and 19) that the southern portion of the Grand Portage follows (Thornberry-Ehrlich 2010). Other ridge-breaks throughout the region are associated with linear weaknesses (faults) which focused weathering, particularly that which occurred by glacial processes (e.g., the gap in the diabase dike referred to at post 17 on the Mt. Rose trail; Phillips 2003).

Ancient Bedrock: Sedimentary Features, Polarity Reversals, and Volcanic Features

"Bedrock" is the solid old rock that underlies the younger unconsolidated surficial and glacial deposits of the monument. Bedrock is exposed in the ridges of diabase (geologic map unit **PCprdb**) crossed by the portage and other areas such as Mount Rose. Bedrock can be sedimentary, igneous, or metamorphic.

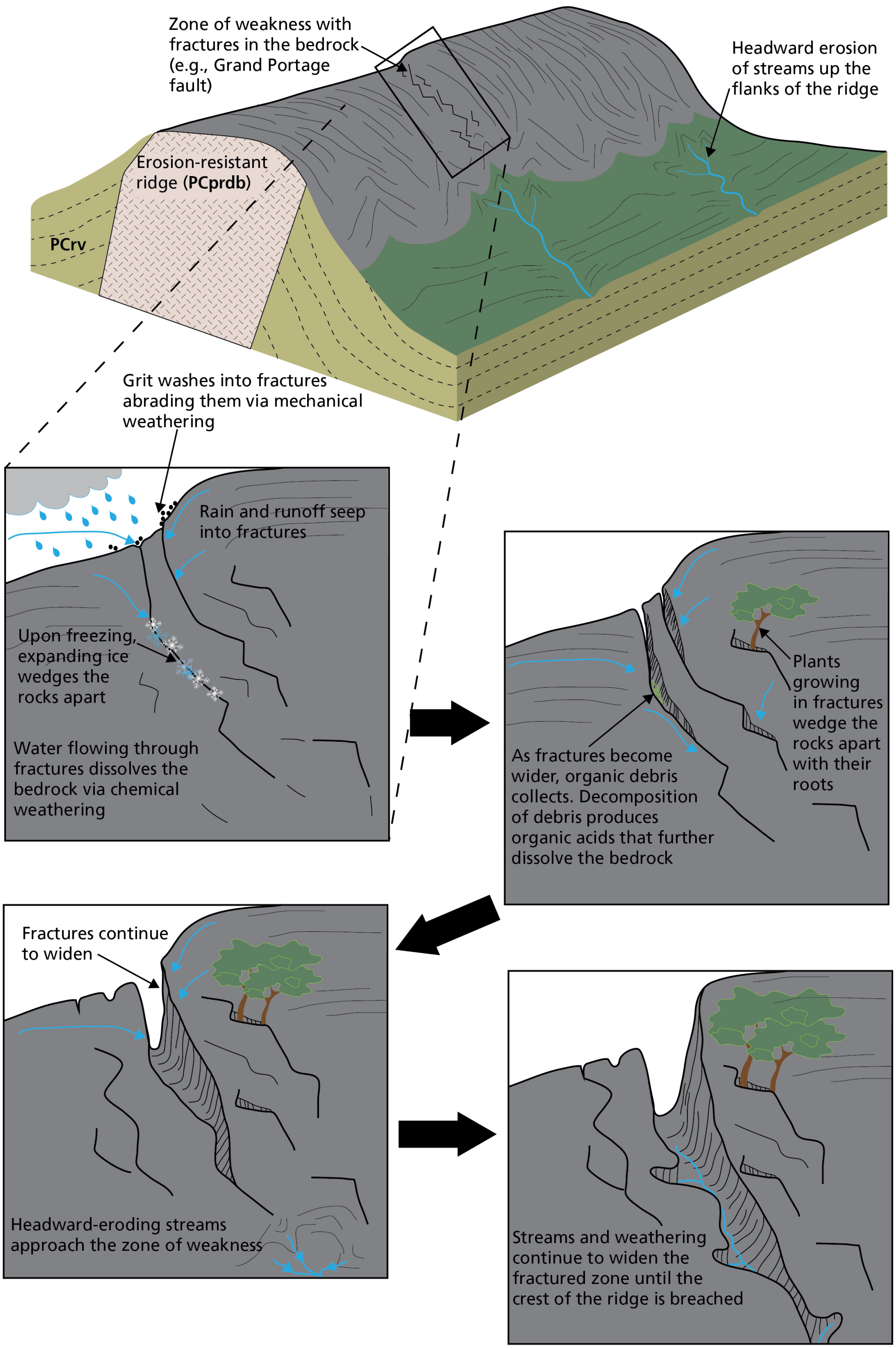

Figure 19. Schematic graphic of gap formation at the outcrop scale. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

Table 3. Clastic sedimentary rock classification and characteristics.

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

Rock Name	Texture	Depositional Environment	Grand Portage National Monument geologic map unit examples
Conglomerate (rounded clasts) Breccia (angular clasts)	Clast size: >2 mm (0.08 in)	Higher Energy (swift river currents; strong winds)	None identified during mapping
Sandstone	Clast size: 1/16–2 mm (0.0025–0.08 in)	Higher Energy (swift river currents; strong winds)	None identified during mapping
Siltstone	Clast size: 1/256–1/16 mm (0.00015–0.0025 in)	Lower Energy (floodplains, lagoons, lakes)	Layers in PCrv
Claystone	Clast size: <1/256 mm (0.00015 in)	Lower Energy (floodplains, lagoons, lakes)	Layers in PCrv

Sedimentary rocks form from fragments of other rocks or chemical precipitation (table 3). Igneous rocks form by the cooling of molten material. Metamorphic rocks are those that have been altered by high temperature, high pressure, and/or fluids. Slightly metamorphosed sedimentary and igneous rocks are present in bedrock outcrops in the monument.

Three main types of sedimentary rocks are clastic, chemical, and organic. Clastic sedimentary rocks are the products of weathering, erosion, transportation, and deposition of rock fragments called "clasts." Chemical sedimentary rocks form when ions (microscopic particles of rock dissolved during chemical weathering) precipitate out of water. Organic sedimentary rocks are composed of organic remains (e.g., coal) or were produced by the physiological activities of an organism (e.g., secretion of calcium carbonate to form limestone of coral reefs). The bedrock within Grand Portage National Monument includes clastic sedimentary layers (see fig. 14; Thornberry-Ehrlich 2010).

The Rove Formation (geologic map unit **PCrv**) is about 975 m (3,200 ft) thick and is a series of graywackes and argillites deposited in deep waters by turbidity (submarine landslide) currents. The sedimentary features of this unit are remarkably well-preserved and offer clues as to the source of the sediment, but the evidence is not conclusive. Ripple marks show a paleocurrent direction to the south which indicates a northern source, however the rocks to the north of Grand Portage are too old (4 billion to 2.5 billion years ago) to be a sediment source for the younger (1.75 million to 1.85 million year old) Rover Formation (Thornberry-Ehrlich 2010).

Much later, about 650 million years after deposition of the Rove Formation, upwelling molten rock caused by a mantle plume resulted in the development of the midcontinent rift and the subsequent intrusion of the other monument geologic map unit, the Pigeon River Diabase (**PCprdb**). Diabase is a dark intrusive igneous rock that is the chemical equivalent to extrusive basalt (e.g., the lava that makes up the Hawaii volcanoes). Fresh exposures have a dark, salt and pepper appearance. Two local, distinct dike swarms are the Grand Portage diabase dikes and the Pigeon River diabase dikes. Minerals within cooling and crystalizing volcanic rocks align with Earth's magnetic field. At various times in Earth history, the magnetic poles were reversed. The Rove Formation (**PCrv**) has reverse magnetic polarity. It was deposited/metamorphosed during the Penokean orogeny, 1.86 billion to 1.81 billion years ago (Schulz and Cannon 2007). The older, Grand Portage diabase dikes cut rift basalts that are 1.105 billion years old and are reversely polarized, which constrains their age to between 1.105 billion to 1.100 billion years ago. The Pigeon River dikes are younger and normally polarized, which means they must be younger than 1,100 million years and are probably about 1,095 million years old—dating from the failed midcontinent rift system (Thornberry-Ehrlich 2010). Intrusion of both sets of dikes into the Rove Formation resulted in contact metamorphism whereby the mineral composition of the host rock changes as a result of the heat associated with the intrusion. Near the intrusion contact, the metamorphic mineral assemblage in the Rove is assigned to a high temperature, low pressure metamorphic facies (pyroxene- and hornblende-hornfels; fig. 20). Local pink stringers rich in sodium and containing sulfide minerals are the result of an introduction of hydrothermal fluids during dike intrusion (Thornberry-Ehrlich 2010). Within the monument, the contact zone contains the mineral cordierite, which geologists use to determine the degree of heating of the country rock during the metamorphic event (Thornberry-Ehrlich 2010).

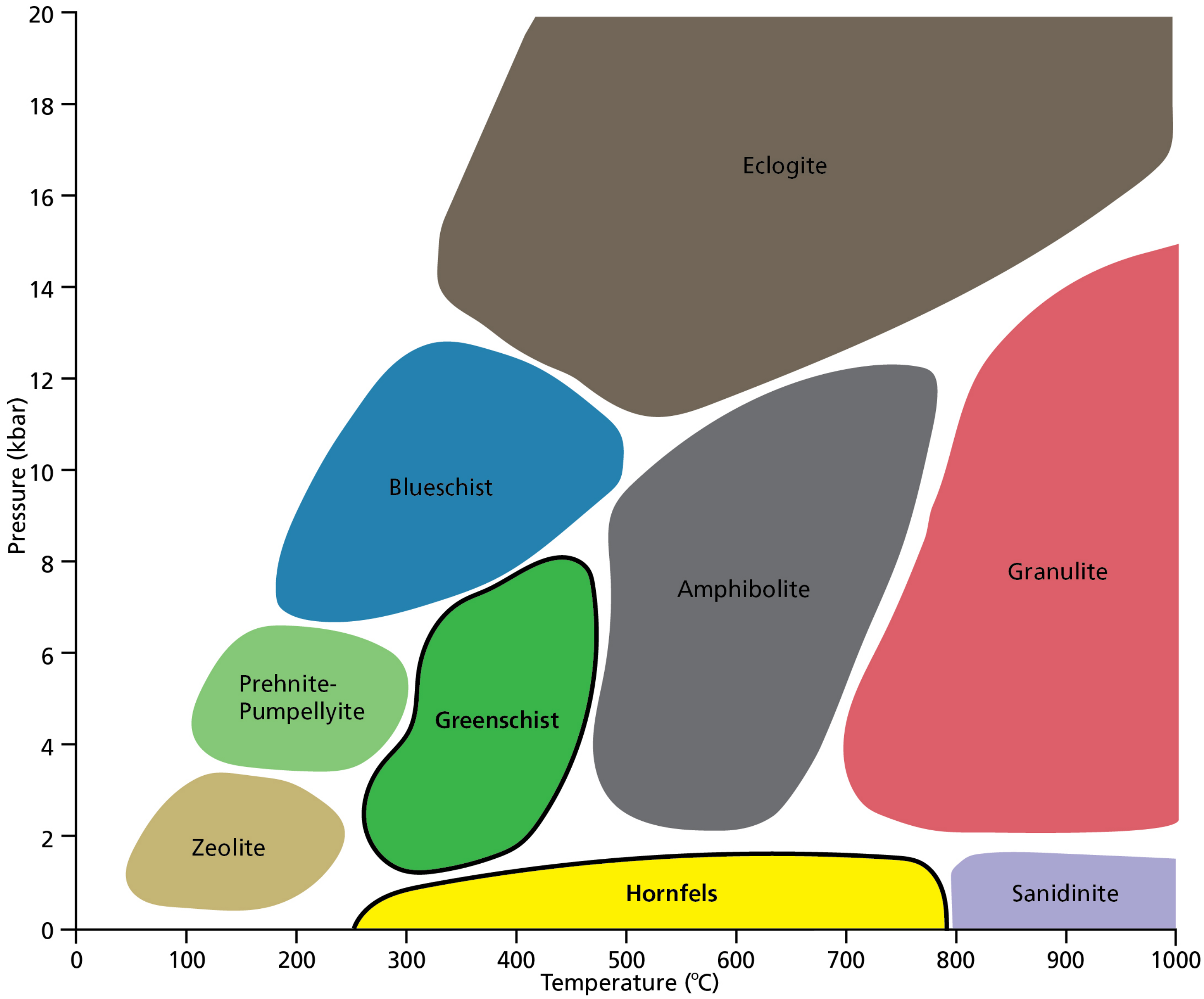

Figure 20. Diagram showing metamorphic facies in pressure-temperature increments.
The area or domain of the graph corresponds to conditions within Earth's crust and upper mantle. The contact zone between the Rove Formation (PCrv) and the intruding Pigeon River Diabase (PCprdb) reached hornfels (yellow field) conditions, suggesting a temperature between approximately 250°C and 800°C (480°F and 1500°F) at a pressure less than 2 kbar (less than 2,000 atm). The entire stack of bedrock at Grand Portage was lightly metamorphosed (perhaps to greenschist facies, suggesting a possible temperature range between approximately 250°C and 450°C [480°F and 840°F] and pressures between approximately 1.5 and 8 kbar [1,500 and 8,000 atm]). Diagram drafted by Trista L. Thornberry-Ehrlich (Colorado State University).

Features within the diabase dikes of the park include chilled margins that formed by quenching of hot magma against the cooler rocks they intruded, and columnar jointing. Columnar joints form by contraction of the rock as it cools and are usually perpendicular to the margins of the dike; this feature is visible near the road at the new visitor center. The erosion resistant dikes of the Pigeon River swarm are much more voluminous than the Grand Portage dikes and support the higher ridges of the region such as Mt. Rose and Mt. Josephine. The dikes form a roughly orthogonal array of northeast-trending and northwest-trending bodies (fig. 21; Thornberry-Ehrlich 2010).

A geologic formation is named for a geographic feature, such as a stream, road, or town located near its type locality, a geographic location where a rock formation is best displayed or first described. More particularly, an outcrop may display the formation so well as to become a reference location referred to as "type section." Type localities and type sections have both scientific and

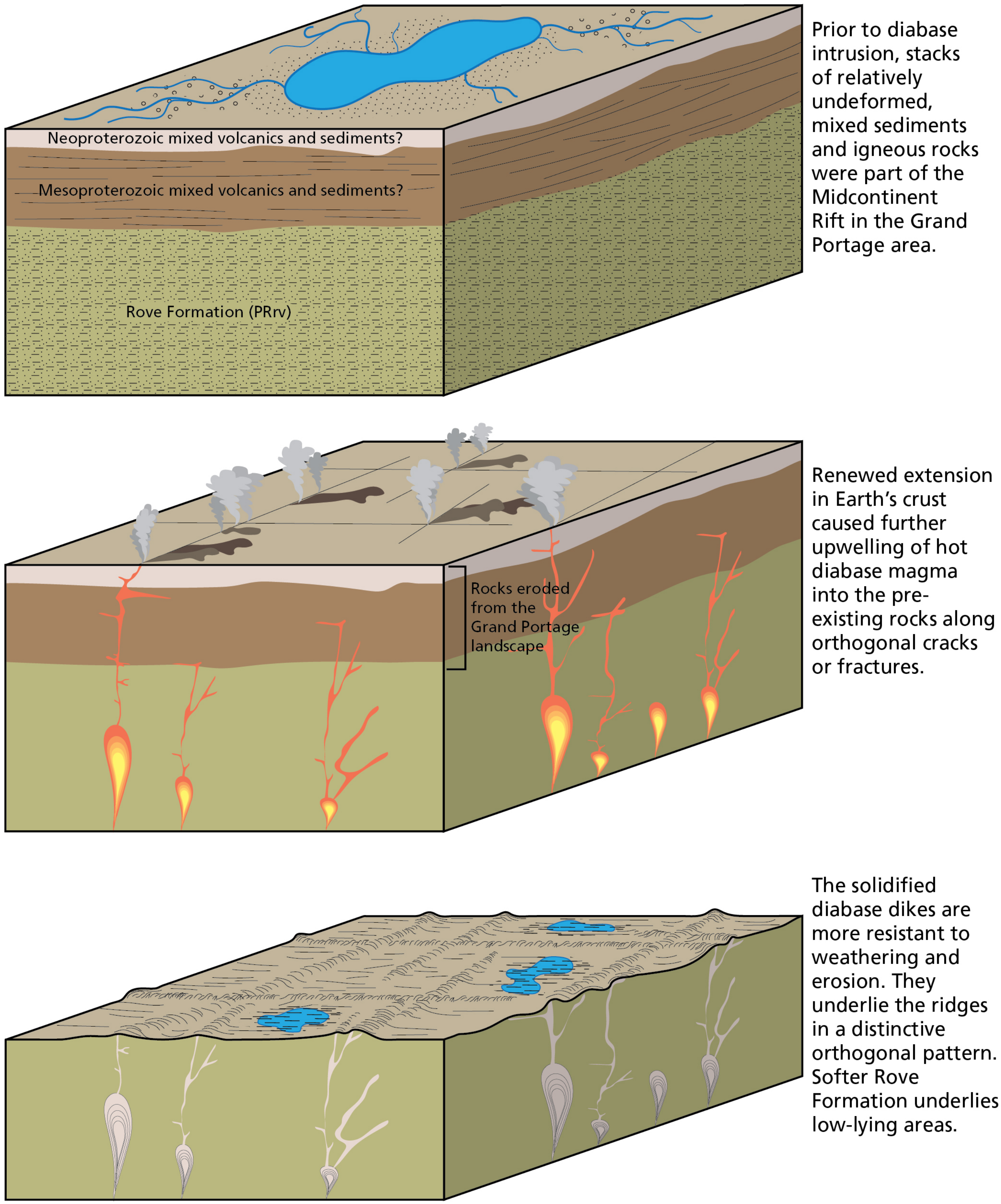

Figure 21. Schematic diagram of the formation of orthogonal ridges in the Grand Portage area. Graphic is by Trista L. Thornberry-Ehrlich (Colorado State University).

educational significance. Because type localities and type sections commonly occur where a formation was originally described and named, they also may have historical significance. The two geologic map unit names (Pigeon River Diabase and the Rove Formation) in the GRI GIS data refer to local geographic features: the Pigeon River and Rove Lake, western Ontario, Canada, just north of the International Boundary. Information about any named geologic unit may be found at the USGS Geolex service: https://ngmdb.usgs.gov/Geolex/search (accessed 30 August 2018).

Paleontological Resource Inventory, Monitoring, and Protection

Paleontological resources (fossils) are any evidence of life preserved in a geologic context (Santucci et al. 2009). All fossils are nonrenewable. Body fossils are any remains of the actual organism such as bones, teeth, shells, or leaves. Trace fossils are evidence of biological activity; examples include burrows, tracks, or coprolites (fossil dung). Fossils in NPS areas occur in rocks or uncgonsolidated deposits, museum collections, and cultural contexts such as building stones or archeological resources. As of April 2019, 271 parks, not including Grand Portage National Monument, had documented paleontological resources in at least one of these contexts. Additional documentation of stromatolites in glacial till within the monument could add the Grand Portage National Monument to that list.

According to the paleontological resources summary prepared by Hunt et al. (2008) for the monument, the Rove Formation (**PCrv**) may contain evidence of microorganisms that are one of the earliest metazoan (animal) life forms on Earth. These appear similar to fecal pellets of zooplankton. Blue green algae remains (stromatolites) occur near Thunder Bay in the Rove Formation; however, the local Rove Formation at Grand Portage National Monument hails from a deeper-water depositional environment. Any stromatolites in the monument would have been part of submarine landslide deposits (turbidites) or present as glacial float transported from elsewhere (e.g., the Gunflint Iron Formation in Ontario; Grand Portage National Monument staff; written communication, 30 January 2019). The monument may also contain fossiliferous glacial erratics, transported in from elsewhere by glacial ice. Paleoecological remains such as pollen may also occur in wetland or glacial lake deposits (Thornberry-Ehrlich 2010). Sediment coring in 2006 in a Beaver Pond revealed the presence of diatoms, but the cores were not systematically surveyed for pollen; further coring in other wetland areas may yield robust pollen records (Edlund 2007). The monument has not yet been systematically assessed for fossils in cultural contexts, but potential exists at archeological sites (Hunt et al. 2008). Ancient stromatolitic jasper was traded throughout the area for tool material, examples of which are in the park collection. The source of this jasper was in the iron formations to the north in Canada (e.g., Gunflint Range; William Clayton, chief of cultural resources, Grand Portage National Monument, conference call, 31 October 2018). The NPS Fossils and Paleontology website, http://go.nps.gov/paleo, provides more information.

Geologic Resource Management

The monument staff collaborate with adjacent landowners, including the Ojibwe, to successfully manage monument resources. This working relationship is a fundamental resource for the monument (National Park Service 2017). The monument's foundation document (National Park Service 2017), resource management plan (National Park Service 1995), general management plan (National Park Service 2003), and natural resource condition assessment (Kraft et al. 2014) are primary sources of information for resource management within the monument. Cultural landscape restoration and management are also addressed in a number of publications, including Thompson (1969), Cockrell (1983), and a cultural landscape report (Bahr Vermeer Haecker Architects/John Milner Associates, Inc. 2009).

The NPS Geologic Resources Division provides technical and policy support for geologic resource management issues in three emphasis areas: (1) geologic heritage, (2) active processes and hazards, and (3) energy and minerals management (see http://go.nps.gov/grd). Monument managers are encouraged to contact the NPS Geologic Resources Division for assistance with the geologic resource management issues listed in this chapter. Monument staff can formally request assistance via the Solution for Technical Assistance Requests ("STAR": https://irma.nps.gov/Star/).

Resource managers may find Geological Monitoring (Young and Norby 2009) useful for addressing geologic resource management issues. The manual provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. Each chapter of Geological Monitoring covers a different geologic resource and includes detailed recommendations for resource managers, suggested methods of monitoring, and case studies. Resource managers may contact the GRI team to request a PDF copy of the manual or individual chapters of the manual. Content is also available on the Geological Monitoring website (https://go.nps.gov/geomonitoring).

The NPS Geologic Resources Division administers the Geoscientists-in-the-Parks (GIP) and Mosaics in Science programs, which provide internships that place scientists (typically undergraduate students) in parks to complete science-related projects. A GIP or Mosaics in Science intern may be able to work on the issues discussed in this chapter. Monument managers are encouraged to contact the NPS Geologic Resources Division about the placement of a geoscience intern in the monument. More information is available at the programs' websites (http://go.nps.gov/gip and http://go.nps.gov/mosaics). GIP projects at Grand Portage National Monument have included (as of April 2018):

- Fluvial surveys, maps, and coring by Kilgore (2012a, 2012b, 2012c, 2012d)
- River and lake terraces by Rosenthal in 2012 (part of GRI GIS data)—these data have been expanded and refined by a cooperative effort between natural resources staff at the monument and a working group within the US Geological Survey using LiDAR. The Minnesota Department of Natural Resources serves 1-m LiDAR data for the entire state at: https://www.dnr.state.mn.us/maps/lidar/index.html. As of October 2018, the US Geological Survey geospatial product is forthcoming.

The Minnesota Geological Survey website (https://www.mngs.umn.edu/) has a wealth of geologic information for the monument area along with digital maps available including bedrock, surficial, and story maps. The survey compiles county geologic atlases; Cook County is a future mapping project for the survey (Terry Boerboom, Minnesota Geological Survey, geologist, conference call, 31 October 2018). Other information available from the survey includes

- County well locations
- County geologic atlases
- Rock property locations
- Drill core logs
- Depth to bedrock
- Measured gravity points
- Magnetic susceptibility logs

Shoreline Erosion

According to Stoddard et al. (2006), the natural historic range of shoreline recession is between 0.07 and 0.29 m/yr (0.23 and 0.95 ft/yr). Any shoreline recession near the historic structures threaten cultural resources at the monument. In 1988, erosion mitigation projects attempted to stem shoreline erosion near the monument's historic features and infrastructure, placing cobbles, geotextile fabric, and planting stabilizing vegetation. The shoreline maintained a somewhat unstable grade, however, even after the cobbles were reworked, the geotextile broke up and flowing water and winter ice have reworked the engineering structures (Thornberry-Ehrlich 2010; Brandon Seitz, Grand Portage National Monument, resource assistant, written communication 24 June 2019). According to the monument's foundation document, the lakeshore was reconstructed and stabilized in 1988, but the overall trend is toward condition deterioration (National Park Service 2017). Hardening the shoreline was suggested to preserve archeological sites (National Park Service 2017). Larger riprap would be necessary; however, armored shorelines in one location may cause increased erosion or negative impacts to adjacent areas (Brandon Seitz, Grand Portage National Monument, biological science technician, written communication, 1 November 2018). Landscaping is ongoing adjacent to the fort on Lake Superior. The overall condition is stable, but native vegetation will be planted in the upland areas and the slope to protect the shoreline and improve the vista (Grand Portage National Monument staff, conference call, 31 October 2018).

Beginning around 2011, monument staff noticed localized shoreline erosion at the eastern end of the monument (fig. 22). A scallop-shaped arc of shoreline was eroding at a rapid pace. At times, the toe of the slope appeared to liquify and slide into the lake via mass wasting (not coastal processes) and an adjacent wetland could drain in the course of just a day (Grand Portage National Monument staff, conference call, 31 October 2018). The land's interaction with groundwater was precipitating the localized erosion; however, the actual cause of the mass wasting remains enigmatic (Brandon Seitz, Grand Portage National Monument, resource assistant, written communication, 1 November 2018). In 2014, the monument submitted a technical assistance request (STAR 1626) to address shoreline erosion. Specifically, the artifact-bearing lakeshore is exposed to high-energy waves along a 137-m- (450 ft-) stretch of shoreline. The height of the bluff or scarp ranges from 2 to 5 m (6 to 16 ft). At this location, lacustrine sands, gravels, and glacial-lake clays make up the landward material. Large trees atop the slope are easily toppled by wind and increase the rate of erosion locally, threatening archeological resources (William Clayton, Grand Portage National Monument, chief of resource management, written communication 14 January 2014). The loss of archeological resources from this erosion is significant because of its potential record of the 18th century fur trade and the almost three centuries of Ojibwe occupation along the north shore of Lake Superior (Seitz 2014). As of 2018, salvage archeology has mitigated the threat from shoreline change and the shoreline loss appears to be slowing. The monument staff prefer to let natural processes reestablish a stable

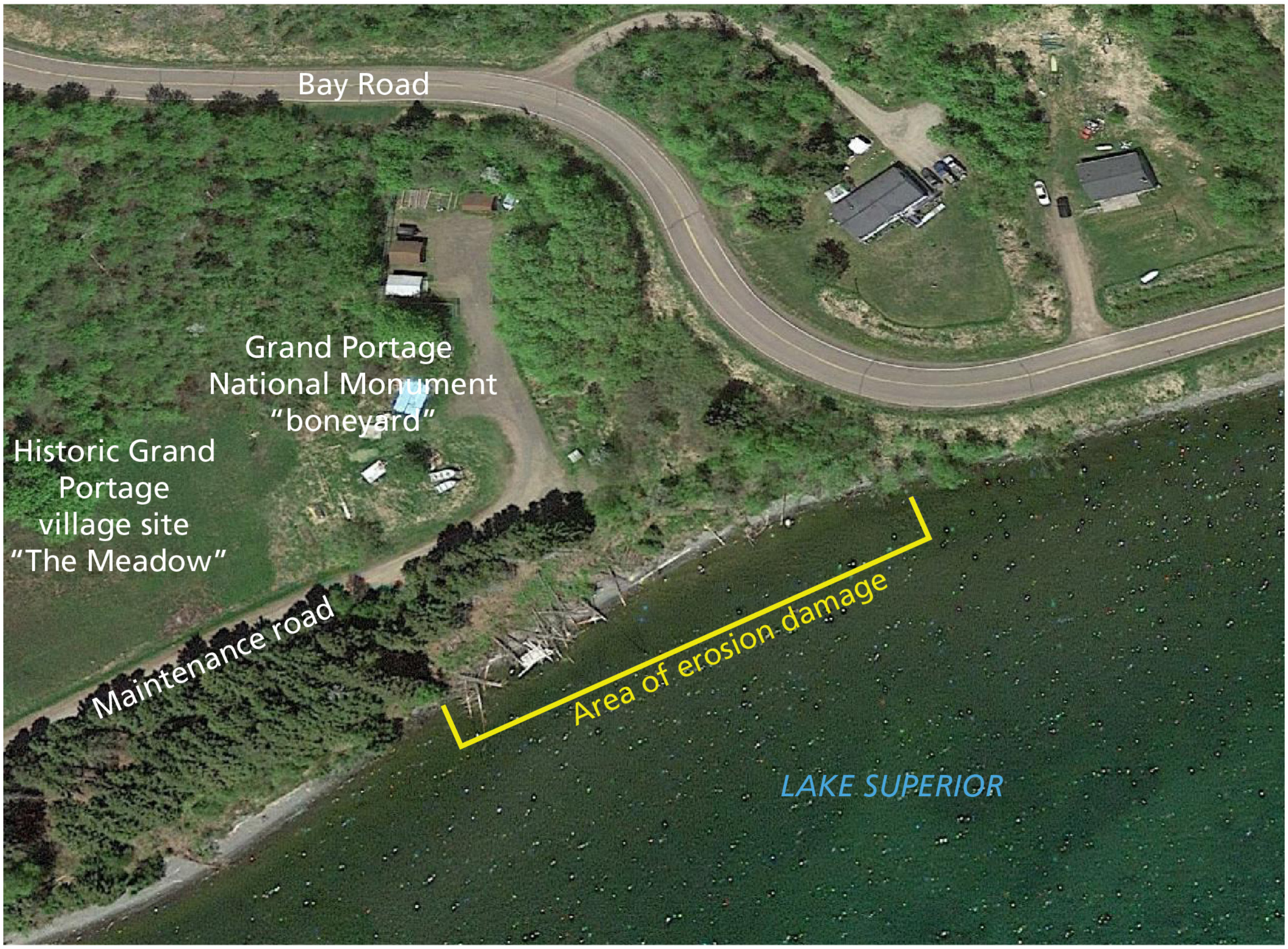

Figure 22. Aerial photograph of erosion damage at the east end of the monument.
Downed trees and scalloped-inward shoreline indicate and area of erosion on the eastern end of the monument near a maintenance area. The erosion was a result of mass wasting as groundwater liquified the lakeshore sediments causing them to slump into the lake and be swept away by waves. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using Google Earth imagery (accessed 15 November 2018).

shoreline (William Clayton, Grand Portage National Monument, chief of resource management, conference call, 31 October 2018).

Geomorphology, regional coastal slope, relative lake level change rate, and mean significant wave height are the four most important factors in coastal vulnerability to lake-level change related to climate change (see "Geologic Significance and Connections" section; Pendleton et al. 2010). Mean annual ice cover, in addition to the factors mentioned above (Phillips 2001; Kraft et al. 2014), are suggested metrics to assess and monitor the vulnerability of the monument.

Potential management resources for shoreline erosion include:

- Phillips (2001 and 2003), which reviewed the geology of the Grand Portage Bay area, as well as shoreline recession rates, prehistoric and historic Lake Superior water levels, and lake level variations caused by weather, climate, and human activities.
- Suggestions from Seitz (2014, quotes from p. 1): "Mitigate or slow down erosional loss of in situ archaeological deposits along the shore. This may include immediate actions based on available resources such as felling trees into Lake Superior and cabling them in place to provide a minimum of protection against further erosional loss." "Conduct an environmental assessment that ties together rehabilitation needs of landscape conservation, archaeological resource preservation and cultural landscape rehabilitation into an actionable

alternative." "Rehabilitate the lakeshore unit by making possible compatible interpretive uses while preserving those portions or features which convey GRPO's historical, cultural and natural resource values."

- Lake level data for Lake Superior maintained by the US Army Corps of Engineers as part of Great Lakes information and lines to NOAA water level gage data: http://www.lre.usace.army.mil/greatlakes/hh/greatlakeswaterlevels/historicdata/greatlakeshydrographs/57T.

Fluvial Erosion, Flooding, and Climate Change Impacts

Seasonal flooding on Grand Portage Creek causes erosion, thereby threatening the integrity of historic structures and stretches of the original Grand Portage trail. Surveys and geomorphic assessments of Grand Portage Creek revealed that the creek naturally shifts across its floodplain over time, but more recent instability is due to land use changes and crossing construction. The most unstable areas of the creek are near bridges and other infrastructure (Kraft et al. 2014). In the 1970s, when fluvial erosion threatened the fort area, stone revetments and car-sized riprap were installed to armor the bank; however, the river has since meandered away from this area. The picnic area adjacent to Grand Portage Creek was under threat until revetments were installed in 1988. Intense weathering inherent in the seasonal conditions, in particular the frigid winters, at Grand Portage National Monument has degraded the revetments, which are now in need of repair (Thornberry-Ehrlich 2010). The 1933 Civilian Conservation Corps stone bridge on Grand Portage Creek is causing local eddies and erosion on one side of the structure. During high flows, the bridge also creates a backwater area and mid-channel gravel bar. Instability associated with the backwater and bar created by the bridges is exacerbated by channelization and revetment downstream that created, or otherwise exaggerated, a longitudinal increase in grade (Fitzpatrick 2017; Brandon Seitz, Grand Portage National Monument, biological science technician, written communication 24 June 2019). According to the monument's foundation document, Poplar Creek is exhibiting increased sedimentation caused by logging and beaver dams; stream flow condition for the creek remains a medium-priority data need (National Park Service 2017).

Kraft et al. (2014) identified the hydrology and geomorphology of Grand Portage Creek, as well as the hydrology of the Pigeon River, to have conditions of moderate concern and uncertain trends. Stream conditions on all but Grand Portage Creek are poorly assessed; better watershed data would allow for better management of fluvial resources at the monument (National Park Service 2017). The foundation document identifies authoring a restoration plan for Grand Portage Creek as a medium-priority management need (National Park Service 2017). Around the ca. 1936 Stone Bridge area, a bio-revetment was installed as an interim treatment until a river rehabilitation product (Martin 2008; Martin and Seitz 2009) comes to fruition (Grand Portage National Monument staff, conference call, 31 October 2018).

As interim guidance, Fitzpatrick (2017) noted:

"In any stream rehabilitation project there is a delicate balance between expected outcomes, geologic setting, and previous human alterations. This is the case with the reaches upstream and downstream of the historic stone bridge over Grand Portage Creek. Based on the previous initial geomorphic interpretation, the following issues need further consideration and monitoring:

- The stone revetment in the channel downstream of historic bridge is causing a more gentle slope upstream and likely causing more water and bedload to accumulate upstream of the historic stone bridge. Consider regrading to more closely match the pre-stabilization thalweg longitudinal profile.
- Upstream of the historic stone bridge, the creek migration into the left bank is being accentuated by buildup of bedload on the right side. This phenomenon was especially noticeable in the Duluth streams at constrictions following the extreme 2012 flood and the Bad River streams following the 2016 flood. In general, the bedload will accumulate and continue to deposit on the bar during flood events. Flows between flood events are not erosive enough to move the deposits on the bar, causing the stream to migrate around the bar and intersect more easily erodible bank deposits.
- As lake levels increase there is potential for the reach near the mouth to form new bars and start to laterally migrate. It appears though the revetment on the right bank is sufficient to sustain higher flows. It would be good to keep an eye out in this area for early detection of any failure. The reach at cross section 1D will likely to continue to erode and could use some attention.
- Tributary contributions of bedload. It might be that the increase in bed material deposition upstream of the bridge is being caused by more coarse material being delivered from nearby tributaries. There is little source or transport of bedload that makes it past the culvert at the Hwy 61 bridge, thus all bed material is derived from Grand Portage Creek channel along

> reaches 2 through 5 or tributaries. The gullying near the baseball field may be contributing excess sediment that is subsequently deposited on the bar upstream of the stone bridge."

On April 28, 2000, collapse of three beaver dams upstream (Tier Lakes Creek) of the portage trail caused a wave of water to surge downstream cutting new, anastomosing channels into the valley floor, rolling freshly moss-free boulders, and piling up debris behind trees and branches (Phillips 2003). Such a catastrophic flood is unusual, but not impossible in the monument streams.

Climate change models predict increased annual average temperature and precipitation. Increases in extreme storms and flooding may damage stream channels and clay-based sections of the portage itself (National Park Service 2017). Some streams (e.g., Pigeon River near Fort Charlotte) are showing earlier snowmelt and peak spring discharge (Kraft et al. 2014), which may impact streambank stability if it occurs prior to spring vegetation taking root.

Resources available for fluvial erosion and climate change impacts include

- The monument's natural resource condition assessment: Kraft et al. (2014).
- Geomorphic study of Grand Portage Creek (potential application to other creeks in the monument): Fitzpatrick 2017 (US Geological Survey technical report forthcoming as of November 2018).
- Stream cross sections and longitudinal profiles: Kilgore (2012a, 2012b, 2012c, 2012d).
- The general management plan (National Park Service 2003) provides zone objectives and desired conditions for the portage corridor.
- The US Geological Survey is conducting an ongoing effort to study the lower Grand Portage Creek (National Park Service 2017).
- Martin (2008) and Martin and Seitz (2009) conducted field assessments of the stability of eroding reaches of the creek and recommended management options.

Geologic Hazards

The University of Minnesota at Duluth has a seismograph. Earthscope serves seismic data and LiDAR as part of its mission to measure motions of Earth's surface and record seismic waves: www.earthscope.org. The NPS Geologic Resources Division Seismic Monitoring website (http://go.nps.gov/seismic_monitoring), and the US Geological Survey Earthquakes Hazards website (http://earthquake.usgs.gov/) provide more information about seismic hazards. In the *Geological Monitoring* chapter about earthquakes and seismic activity, Braile (2009) described the following methods and vital signs for understanding earthquakes and monitoring seismic activity: (1) monitoring earthquakes, (2) analysis and statistics of earthquake activity, (3) analysis of historical and prehistoric earthquake activity, (4) earthquake risk estimation, (5) geodetic monitoring and ground deformation, and (6) geomorphic and geologic indications of active tectonics.

The following references provide additional background information, suggested vital signs, and resources for assessing and documenting slope movements:

- In the Geological Monitoring chapter about slope movements, Wieczorek and Snyder (2009) described five vital signs for understanding and monitoring slope movements: (1) types of landslide, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessment of landslide hazards and risks.
- US Geologic Survey publication: The landslide handbook—A guide to understanding landslides (Highland and Bobrowsky 2008)
- US Geological Survey landslides website (http://landslides.usgs.gov/)
- NPS Geologic Resources Division Geohazards website (http://go.nps.gov/geohazards)
- NPS Geologic Resources Division Slope Movement Monitoring website (http://go.nps.gov/monitor_slopes)
- Natural hazards science strategy: Holmes et al. (2013)
- Landslide hazards and climate change: Coe (2016)

Habitat integrity and disturbed lands

Fundamental resources listed in the monument's natural resource condition assessment include beaver habitats, southern boreal forest, and the Pigeon River. These all have strong connections with listed geologic features and processes such as riparian habitat, wetland habitat, sediment retention, and hydrological processes (Kraft et al. 2014).

National Park Service (1995) identified roads in need of removal and the foot traffic disturbing the ground at Fort Charlotte as resource management concerns and needs. Development along Lake Superior also threatens to impact cultural landscapes, vistas, and natural habitats (National Park Service 1995).

Isotopic analyses of mercury concentrated in monument soils revealed it to stem from 18th-century trade of vermilion for dyes, paint, cosmetics, etc. (Rolfhus and Seitz 2017). Mercury concentrations are significant enough to consider formal remediation (Rolfhus et al. 2015; Rolfhus and Seitz 2017; Grand Portage National Monument staff, conference call, 31 October 2018). Park staff are currently working with a Department of Interior industrial hygienist who has been tasked with determining whether personal protective equipment should be worn during ground disturbance activities (Grand Portage National Monument staff, conference call, 31 October 2018). The Midwest Regional office (contact Jim Conroy, environmental engineer, jim_conroy@nps.gov) is working closely with park staff to navigate responsibilities under the Comprehensive Environmental Response, Compensation, and Liability Act (Brandon Seitz, Grand Portage National Monument, biological science technician, written communication 24 June 2019). The NPS Disturbed Lands Restoration website, https://www.nps.gov/articles/geoconservation-disturbed-land-restoration.htm provides further information.

Paleontological resource inventory, monitoring, and protection

Grand Portage National Monument has the potential for fossils in rocks or unconsolidated deposits or cultural contexts. All paleontological resources are nonrenewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act. The monument's resource management plan identifies preserving and protecting paleontological resources as a primary resource management goal (National Park Service 1995). Monument staff expressed great interest in obtaining lake cores for their palynological record. The St. Croix Watershed Research Station (https://www.smm.org/scwrs) maintains a core repository as may the Natural Resources Research Institute at the University of Minnesota Duluth (https://www.nrri.umn.edu/) (Terry Boerboom, geologist, Minnesota Geological Survey, conference call, 31 October 2018).

Hunt et al. (2008) prepared a paleontological resource summary for the parks of the Great Lakes Network, including Grand Portage National Monument. The summary was compiled through extensive literature reviews and interviews with park staff and professional geologists and paleontologists, but no field-based investigations. An on-the-ground paleontological survey would be an ideal GIP project. Resource-management recommendations from Hunt et al. (2008) for the monument included

- Encourage park staff to observe exposed gullies, other erosional bedrock, and streams for fossil material while conducting their usual duties.
- Photodocument and potentially monitor any occurrences of paleontological resources that may be observed in situ.
- Consider long-term monitoring of paleontological sites.
- Contact the NPS Geologic Resources Division for paleontological resource management assistance.

Other resources for guidance on paleontological issues include

- The NPS Fossils and Paleontology website, http://go.nps.gov/paleo.
- Kenworthy and Santucci (2006) presented a summary of National Park Service fossils in a cultural resource context.
- Santucci et al. (2009) details paleontological resource monitoring strategies.

Geologic Map Data

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

Geologic Maps

A geologic map is the fundamental tool for depicting the geology of an area. Geologic maps are two-dimensional representations of the three-dimensional geometry of rock and sediment at or beneath the land surface (Evans 2016). Colors and symbols on geologic maps correspond to geologic map units. The unit symbols consist of an uppercase letter indicating the age (see table 1) and lowercase letters indicating the formation's name. Other symbols depict structures such as faults or folds, locations of past geologic hazards that may be susceptible to future activity, and other geologic features. Anthropogenic features such as mines or quarries, as well as observation or collection locations, may be indicated on geologic maps. The American Geosciences Institute website, http://www.americangeosciences.org/environment/publications/mapping, provides more information about geologic maps and their uses.

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

Source Maps

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

- Pigeon Point Quadrangle: Mudrey (1977); map code "pipo"
- Duluth Complex: Miller et al. (2001); map code "grpo"
- Terraces: Rosenthal (2012); map code "grpo"

This report is supported by maps of the bedrock geology and lake terrace of Grand Portage National Monument. The maps were developed by two different groups covering different areas. The Pigeon Point quadrangle map, map code "pipo", is beyond monument boundaries, but within its area of interest. This large-scale map displays more detail than the Duluth Complex map (map code "grpo", clipped to the Grand Portage quadrangle boundaries). Lake terraces and some surficial information were captured by Rosenthal (2012) and are part of map code "grpo" data. No known detailed surficial map coverage of the monument exists.

GRI GIS Data

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

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

The following components are part of the data set:

- A GIS readme file (grpo_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information.
- Data in ESRI geodatabase GIS format;
- Layer files with feature symbology (table 4);

- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information document (grpo_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures;
- ESRI map documents (grpo_geology.mxd and pipo_geology.mxd) that display the GRI GIS data; and
- A version of the data viewable in Google Earth (grpo_geology.kmz and pipo_geology.kmz; table 4).

Table 4. GRI GIS data layers for Grand Portage National Monument.

Data Layer	On Poster?	Google Earth Layer?
Map Symbology	No	No
Mine Point Features	No	No
Mineral Occurrences	No	No
Point Geologic Units	No	No
Alteration and Metamorphic Area Boundaries	No	No
Alteration and Metamorphic Areas	No	Yes
Geologic Line Features	No	Yes
Linear Dikes	No	Yes
Faults (both grpo and pipo)	Yes	Yes
Former Lake Superior Levels	Yes	Yes
Terrace Area Boundaries	Yes	No
Terrace Areas	Yes	Yes
Lake Terrace Areas	Yes	Yes
Linear Dikes and Sills	Yes	Yes
Geologic Attitude Observation Localities (both grpo and pipo)	No	No
Geologic Contacts (both grpo and pipo)	Yes	Yes
Geologic Units (both grpo and pipo)	Yes	Yes

GRI Map Poster

A poster of the GRI GIS draped over a shaded relief image of the monument and surrounding area is included with this report. Not all GIS feature classes are included on the poster (table 4). Geographic information and selected monument features have been added to the poster. Digital elevation data and added geographic information are not included in the GRI GIS data but are available online from a variety of sources. Contact GRI for assistance locating these data.

Use Constraints

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

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features on the poster. Based on the source map scales (1:200,000 and 1:24,000) and US National Map Accuracy Standards, geologic features represented in the geologic map data are expected to be horizontally within 102 m (333 ft) and 12 m (40 ft) of their true locations, respectively.

Further Geologic and GIS Data Needs and Sources

The GRI GIS data is restricted to bedrock coverage with some surficial information about river and lake terraces.

- Detailed surficial mapping (including paleolakeshores/paleobeaches) is a pressing resource management need at the monument.
- Core data for Quaternary deposits would reveal much about the more recent landscape history.
- The most recent National Park Service boundary GIS layer is available at: https://irma.nps.gov/DataStore/Reference/Profile/2225713.
- According to National Park Service (2017), many monuments marking the park boundary are missing or not yet located. This caused timber trespasses decades ago. Boundary survey and marking is a

high-priority management need and ongoing by the Midwest Region and monument staff.

- Gafvert (2009b) listed the available geospatial data layers for landcover and land use analyses, including recent aerial photographs, high resolution satellite imagery, and LiDAR.
- Ascertain subsurface ownership by contacting the Minnesota Department of Natural Resources regarding mineral rights, as well as the NPS Geologic Resources Division.

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

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Additional References

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

Geology of National Park Service Areas

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

NPS Resource Management Guidance and Documents

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

Climate Change Resources

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

Geological Surveys and Societies

- Minnesota Geological Survey: http://www.mngs.umn.edu/
- US Geological Survey: http://www.usgs.gov/
- Geological Society of America: http://www.geosociety.org/
- American Geophysical Union: http://sites.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: http://www.stategeologists.org/

US Geological Survey Reference Tools

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

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting, held on 21 July 2010, or the follow-up report writing conference call, held on 31 October 2018. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://go.nps.gov/gripubs.

2010 Scoping Meeting Participants

Name	Affiliation	Position
Eric Carson	Wisconsin Geological Survey	Geologist
Jim Chappell	Colorado State University	Geologist
Ulf Gafvert	NPS Great Lakes Network	Data manager
Bruce Heise	NPS Geologic Resources Division	Geologist
Jason Kenworthy	NPS Geologic Resources Division	Geologist, GRI reports coordinator
Richard Ojakangas	University of Minnesota (Duluth)	Geologist
Jamie Robertson	Wisconsin Geological Survey	Geologist
Brandon Seitz	NPS Grand Portage National Monument	Biological science technician
Trista Thornberry-Ehrlich	Colorado State University	Geologist, report writer, graphic designer
Julie Van Stappen	NPS Apostle Islands National Lakeshore	Natural resources branch chief
Laurel Woodruff	US Geological Survey	Geologist

2018 Conference Call Participants

Name	Affiliation	Position
Michael Barthelmes	Colorado State University	Geologist, report writer/editor
Terry Boerboom	Minnesota Geological Survey	Geologist
Jim Chappell	Colorado State University	Geologist, GIS specialist
Bill Clayton	NPS Grand Portage National Monument	Chief of resources management
Craig Hansen	NPS Grand Portage National Monument	Superintendent
Mark Hart	NPS Great Lakes Network	Data manager
Jason Kenworthy	NPS Geologic Resources Division	Geologist, GRI reports coordinator
Al Kirschbaum	NPS Great Lakes Network	GIS remote sensing specialist
Brandon Seitz	NPS Grand Portage National Monument	Biological science technician
Trista Thornberry-Ehrlich	Colorado State University	Geologist, report writer, graphic designer
Stephen Veit	NPS Grand Portage National Monument	Museum technician

Appendix B: Geologic Resource Laws, Regulations, and Policies

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

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/Agriculture to identify “significant caves” on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester. **National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of cave and karst resources. **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be cancelled with appropriate compensation; and lands are withdrawn from mineral entry.	**36 CFR § 2.1** prohibits possessing/ destroying/disturbing…cave resources…in park units. **43 CFR Part 37** states that all NPS caves are “significant” and sets forth procedures for determining/ releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/ adjacent to wilderness.
Paleontology	**National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa et seq.** provides for the management and protection of paleontological resources on federal lands.	**36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted. **43 CFR Part 49** (in development) will contain the DOI regulations implementing the Paleontological Resources Preservation Act.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Recreational Collection of Rocks Minerals	**NPS Organic Act, 54 USC. § 100101 et seq.** directs the NPS to conserve all resources in parks (which includes rock and mineral resources) unless otherwise authorized by law. **Exception: 16 USC. § 445c (c)** Pipestone National Monument enabling statute. Authorizes American Indian collection of catlinite (red pipestone).	**36 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units. **Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown. **Exception: 36 C.F.R. § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, and Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
Geothermal	**Geothermal Steam Act of 1970, 30 USC. § 1001 et seq. as amended in 1988**, states ● No geothermal leasing is allowed in parks. ● "Significant" thermal features exist in 16 park units (the features listed by the NPS at **52 Fed. Reg. 28793-28800** (August 3, 1987), plus the thermal features in Crater Lake, Big Bend, and Lake Mead). ● NPS is required to monitor those features. ● Based on scientific evidence, Secretary of Interior must protect significant NPS thermal features from leasing effects. **Geothermal Steam Act Amendments of 1988, Public Law 100--443** prohibits geothermal leasing in the Island Park known geothermal resource area near Yellowstone and outside 16 designated NPS units if subsequent geothermal development would significantly adversely affect identified thermal features.	None applicable.	**Section 4.8.2.3** requires NPS to ● Preserve/maintain integrity of all thermal resources in parks. ● Work closely with outside agencies. ● Monitor significant thermal features.

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

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

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

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

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

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

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

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