National Park Service
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Natural Resource Stewardship and Science

Pictured Rocks National Lakeshore

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2022/2421

ON THE COVER
Photograph of the moon shining over the Pictured Rocks cliffs. Water seeping through the bedding planes within the cliffs causes staining when dissolved minerals precipitate out of solution along the rock faces. Different minerals cause different stain colors. Lake cruises skirt the base of the cliffs at Pictured Rocks National Lakeshore.
Photograph by Trista L. Thornberry-Ehrlich (Colorado State University) taken in summer 2010.

THIS PAGE
Photograph of Sable Creek tumbling down Sable falls through its steep channel toward Lake Superior. Isostatic rebound following melting of thick glacial ice about 10,000 years ago is creating short, steep drainages flowing toward the lake basin.
Photograph by Trista L. Thornberry-Ehrlich (Colorado State University) taken in summer (2010).

Pictured Rocks National Lakeshore

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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 2020. Chapters of this report describe the geologic setting and history leading to the present-day landscape, discuss the distinctive geologic features and processes within Pictured Rocks National Lakeshore, highlight geologic issues facing resource managers with references to further information, and provide information about the previously completed GRI GIS data.

Established on 5 October 1972, Pictured Rocks National Lakeshore (referred to as the "lakeshore" throughout this report) preserves and protects the natural and cultural resources along more than 62 km (37 mi) of Lake Superior shoreline between Munising and Grand Marais in the upper peninsula of Michigan. The stunning Pictured Rocks cliffs rise above the dark blue waters of Lake Superior. Their colorful stripes are the result of water flowing through the bedrock, dissolving minerals as it passes, then precipitating those minerals where it seeps out of the cliff face.

The lakeshore includes more than just the towering cliffs, it preserves a long geologic history of landscape development. Among the myriad features within the lakeshore are sea cliffs and high bluffs, sea caves, pinnacles, terraces, arches, beaches, and waterfalls, as well as inland features such as lakes and kettle ponds, rivers, sand dunes, and glacial till and outwash deposits. The Grand Sable banks support an active dune field that is among the finest examples of perched dunes, or dunes that form atop a cliff or bluff, in the world.

This report is supported by GIS data sets of the surficial and bedrock geology of the lakeshore. The two data sets were compiled by the GRI team in 2022 from five source publication maps. The source maps were developed by different groups (Michigan Department of Natural Resources, Michigan Geological Survey, and Western Michigan University) using distinct methodologies and resulting in unique data sets. The bedrock was mapped at a coarse scale with a limited number of relatively undeformed sedimentary rock layers, the oldest of which formed more than a billion years ago. The bedrock is largely buried by surficial units comprising glacial and post-glacial deposits. These are generally less than 100,000 years old; some are still forming today. The map of surficial units was completed at a finer scale using field mapping and auger-boring data. The GRI GIS data sets may be updated if new, more accurate geologic maps become available or if software advances require an update to the digital format.

The geologic units within the lakeshore reveal a long geologic history stretching back more than a billion years. The oldest unit, the Jacobsville Sandstone (geologic map unit **Yj**), was deposited in a series of braided streams and shallow lakes on the flanks of a valley that was the setting of a failed continental rift in the ancient North American continent (or "craton"). Volcanic rocks associated with the rift, analogous to the modern East African Rift, are buried beneath the sandstone. Following a period of erosion or nondeposition, the sedimentary rocks of the Munising, Trempealeau, and Au Train Formations (**Cm**, **Ct**, and **Oat**, respectively) were deposited during the Cambrian and Ordovician Periods (538.8 million to 443.8 million years ago; International Commission on Stratigraphy 2022). These units were buried but are now exposed at the surface following hundreds of millions of years of erosion and weathering.

The GRI GIS data include the Trempealeau Formation (**Ct**) above the Munising Formation (**Cm**); however, review of fossil evidence and research of other sources preclude the presence of a Trempealeau Formation in the Pictured Rocks National Lakeshore area. The so-called Trempealeau interval belongs to one of the other units. From its dolomitic sandstone composition and position capping the Miners Castle Member of the Munising Formation, it appears to be part of the lower Au Train (Justin Tweet, National Park Service, paleontologist, written communication, 28 July 2020). The GRI map team is investigating the possibility of updating bedrock mapping with a more accurate and detailed source scale and to clarify these geologic map unit discrepancies. This report reflects the existing GRI

GIS data (map product) while identifying the need for more accurate source map information.

During the Pleistocene Epoch (2.58 million to 11,700 years ago), glaciers scoured the bedrock and left a series of glacial deposits across the local landscape. These deposits include drumlins (surficial geologic map unit **Qdr**); eskers (**Qe**); stacked push moraines (**Qpm**); the Munising outwash fan complex (**Qm**); the Grand Marais outwash fan complex (**Qg**); outwash, undifferentiated (**Qsg**); meltwater sluiceways (**Qs**); kame terraces (**Qkt1–6**); and diamicton (unsorted sediments with a range of particle sizes; e.g., till) ridges (**Qd**). After the glaciers melted away, a series of glacial lakes occupied the basin. One of these, during the transgressive Nipissing phase (highstand), left shoreline marks and terraces at the lakeshore above the current lake level. Since the Pleistocene Epoch, Earth surface processes have continued to modify the landscape. Peat and muck (**Qp**) accumulate in marshes and swamps. Beach sand (**Qb**) is stirred and moved by the waves and wind whips sand into dunes. Changing lake levels modify the shoreline and erosion of coastal bluffs and cliffs contribute sand to coastal systems. Human alterations to the landscape resulted in disturbed land such as sand or gravel pits (**Qdl**).

Geologic features, processes, and resource management issues identified during the GRI scoping meeting and follow-up conference call include the following:

- Pictured Rocks. The Pictured Rocks cliffs, stained with colorful precipitated mineral seeps, are the premier attraction to the lakeshore. Several waterfalls cascade down their face. Lakeshore outcrops are exceptionally well exposed for observation.
- Sedimentary Rock Features. The rocks that form the foundation of Pictured Rocks National Lakeshore contain many features indicative of their geologic history. The Mesoproterozoic and early Paleozoic sedimentary rocks are among the oldest in Michigan. They collected in braided streams and shallow ponds of a failed rift valley and later in shallow to deep basins.
- Lake Superior Shoreline. Shorelines within the lakeshore are extremely dynamic. Along its length, the shoreline within the lakeshore experiences a wide variety of wave energies, ranging from exposed, high-energy locations to sheltered, low-energy sites. Waves sculpt bedrock shores into sea caves, arches, stacks, and cliffs. Bluffs or banks form where waves reach portions underlain by thick glacial deposits. In low-energy areas, sand collects in beaches. The shorelines at the lakeshore are vulnerable to impacts from lake-level changes. Lake levels are controlled by factors including climate, local uplift or subsidence, and land use. Lake-level change associated with climate change is a primary resource management concern at the lakeshore because much of the natural resources, fragile habitats, and visitor access areas are within a few meters of the shore.
- Surficial Deposits. Unconsolidated surficial deposits are being deposited and reworked on the landscape. These deposits include beach sand (**Qb**) as well as organic sediment such as peat and muck (**Qp**), which collects in quiet water lagoons, kettles, and bogs.
- Aeolian Features and Processes. Windblown erosion, transportation, and deposition of sediments have led to the formation of dunes, barriers, and sand spits at Pictured Rocks National Lakeshore. Sand is blasted from the exposed faces of beaches and bluffs by the local winds. These beaches and bluffs serve as vital sources of sediment.
- Fluvial Features and Processes. Most of the rivers in the lakeshore are short with steep channels. Larger rivers throughout the region are important contributors of sediment to the regional lakeshore system. Fluvial processes continuously reshape the landscape. As the larger streams meander across their floodplains, they erode into the unconsolidated deposits flanking their channels and cause undercutting and slope movements.
- Inland Lacustrine Features and Processes and Wetlands. Water bodies inland of Lake Superior at the lakeshore are commonly kettles formed as blocks of stranded glacial ice were buried, then melted in place to form a depression. Other features formed as lagoons when wave action on Lake Superior blocked a stream outlet, which then flooded an area. Wetlands are shown as peat and muck (**Qp**) in the GRI GIS data.
- Glacial Features. Glaciations affected the landscape in two major ways: (1) created or carved features into the landscape, and (2) deposited mantles of sediment over the landscape. Glaciers movement scoured the Lake Superior basin. Drumlins (**Qdr**), push moraines (**Qpm**), and grooves provide information about which direction the glaciers flowed. Glacial deposits in the lakeshore are of two types: (1) those deposited directly by moving ice, and (2) those deposited by meltwater in rivers (glaciofluvial outwash) or lakes (glaciolacustrine).
- Geologic Hazards. Slope movements (the downslope transfer of earth materials) occur as small-scale landslides, slumps, and slope creep on the steep bluffs. The bedrock cliff areas are prone to block fall, topple, and slides. Erosion is constantly changing the land surface. Where vegetation is disturbed by human activities or where infrastructure is at risk, slope movements can become an issue. Natural slope

processes are to be expected on the shorelines under the onslaught of constant wave action. Geologic, morphological, physical, and anthropogenic factors contribute to slope instability and erosion. The mitigation of slope hazards, limited to areas where historic structures (e.g., light stations) are threatened, may involve the construction of stabilizing structures to protect cultural resources and visitor access.

- Climate change is predicted to increase air and water temperatures, change precipitation patterns, and reduce overall winter ice. These changes will in turn impact the natural ecosystems and cultural resources within and surrounding the lakeshore, as well as recreational opportunities and visitor health.
- Disturbed Lands. The lakeshore includes a long history of human use. Most disturbed features are being allowed to naturally return to a state of equilibrium. Some are interpreted for visitors. Disturbed land in the form of gravel and/or sand pits (**Qdl**) occur within the lakeshore boundary.
- Paleontological Resources Inventory, Monitoring, and Protection. Fossils are evidence of life preserved in a geologic context. The ancient bedrock of the lakeshore contains Cambrian and Ordovician fossils. Glacial deposits in the lakeshore also contain fossils. Discovery of Pleistocene and Holocene fossils is possible at the lakeshore, but none are currently documented. Remains of past life could wash onto the shorelines or occur within peat (**Qp**). The lakeshore lacks a field-based paleontological resource survey. Such a survey could provide detailed, site-specific descriptions and resource management recommendations for paleontological resources at the lakeshore.

Products and Acknowledgments

The NPS Geologic Resources Division (GRD) partners with the Colorado State University Department of Geosciences and University of Alaska Museum of the North to produce GRI products. The Michigan Department of Natural Resources, Western Michigan University, and Michigan Geological Survey developed the source maps and reviewed GRI content. This chapter describes GRI products and acknowledges contributors to this report.

GRI Products

Starting in 2010, the GRI team—which is a collaboration between GRD staff and research associates at Colorado State University, Department of Geosciences, and the University of Alaska Museum of the North—completed the following three tasks as part of the GRI for the lakeshore: (1) conducted a scoping meeting and provided a scoping summary (2) provided digital geologic map data in a geographic information system (GIS), and (3) provided a GRI report (this document). GRI products are available on the GRI publications website http://go.nps.gov/gripubs and through the NPS Integrated Resource Management Applications (IRMA) portal https://irma.nps.gov/. Enter "GRI" as the search text and select a park from the unit list. Additional information regarding the GRI, including contact information, is available at http://go.nps.gov/gri.

GRI Scoping Meeting

On 23 July 2010, the National Park Service held a scoping meeting at the lakeshore in Munising, Michigan. The scoping meeting brought together park staff and geologic experts, who reviewed and assessed available geologic maps, developed a geologic mapping plan, and discussed geologic features, processes, and resource management issues to be included in the final GRI report. A scoping summary (Thornberry-Ehrlich 2010) summarizes the findings of that meeting.

GRI GIS Data and Poster

Following the scoping meeting, the GRI team compiled two GRI GIS data sets—bedrock geology and surficial geology—for the lakeshore from five source maps. These data are available for download on IRMA at https://irma.nps.gov/DataStore/Reference/Profile/2175788. This report was written to the GRI GIS data sets that were compiled in 2022. The GRI GIS data may be updated if new, more accurate geologic maps become available or if software advances require an update to the digital format.

VanderMeer et al. (2020) provided a poster of the surficial geology draped over a hillshade of the lakeshore and surrounding area. The surficial unit names and symbols are the same between the GRI GIS data and poster except for the following: (1) GRI map unit **Qdl** is "**pit**" on the poster and (2) GRI map unit **OCPRbr** is "**R**" (bedrock) on the poster. Because these data are the principal deliverable of the GRI, a more detailed description of the products are provided in the "Geologic Map Data" chapter of this report.

The bedrock GRI GIS data include the Trempealeau Formation (**Ct**) above the Munising Formation (**Cm**); however, review of fossil evidence and research of other sources preclude the presence of a Trempealeau Formation in the Pictured Rocks National Lakeshore area (Justin Tweet, National Park Service, paleontologist, written communication, 28 July 2020). The GRI team is investigating the possibility of updating bedrock mapping with a more accurate and detailed source scale and to correct these geologic map unit discrepancies. This report reflects the existing GRI GIS data while identifying the need for more accurate source map information.

GRI Report

On 29 July 2020, the GRI team hosted a follow-up conference call for park staff and interested geologic experts. The call provided an opportunity to get back in touch with park staff, introduce "new" (since the 2010 scoping meeting) staff to the GRI process, and update the list of geologic features, processes, and resource management issues for inclusion in the final GRI report.

This report is a culmination of the GRI process. It synthesizes discussions from the scoping meeting in 2010, the follow-up conference call in 2020, and additional geologic research. The selection of geologic features was guided by the previously completed GRI map data, and writing reflects the data and interpretation of the source map authors. Information from the lakeshore's foundation document (National Park Service 2016) was also included as applicable to the lakeshore's geologic resources and resource management.

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.

Acknowledgments

The GRI team thanks the participants of the 2010 scoping meeting and 2020 follow-up conference call for their assistance in this inventory. The lists of participants (below) reflect the names and affiliations of these participants at the time of the meeting and call. Because the GRI team does not conduct original geologic mapping, we are particularly thankful for the Michigan Department of Natural Resources, Western Michigan University, and the Michigan Geological Survey for their geologic maps of the area. This report and accompanying GIS data could not have been completed without them. Additional thanks to Kyle Hinds and Sarah Russell (NPS Geologic Resources Division) for their review of the abandoned mineral lands section.

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Geologic Setting and Significance

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

Lakeshore Establishment

As the deepest, coldest, and largest body of freshwater in North America, Lake Superior is the most pristine of the Great Lakes (National Park Service 2016). The lake is graced with thousands of miles of dramatic shoreline. Part of this shoreline includes Pictured Rocks—the dramatic sandstone cliffs that appear painted because of the colorful stripes of mineral precipitates decorating their surface. Pictured Rocks National Lakeshore, authorized on 15 October 1966 and established on 5 October 1972 as the nation's first national lakeshore, preserves and protects more than 60 km (40 mi) of southern Lake Superior shoreline in northern Michigan. Characteristic of this stretch of shoreline are high bluffs, sea cliffs, sea caves, wave-cut benches, waterfalls, arches, sand banks, and dunes that attracted 1.2 million visitors in 2020. Visitation increased by more than 30% between 2011 and 2015 as a result of better access via county roads, State of Michigan marketing, and warming local climate (National Park Service 2016). The total area contained within the lakeshore is 29,637 ha (73,235 ac), of which 25,545 ha (63,122 ac) are terrestrial; the boundary of the lakeshore extends 0.40 km (0.25 mi) offshore on the lake surface (fig. 1). The lakeshore also includes two small units in the populated places of Munising and Grand Marais, Michigan.

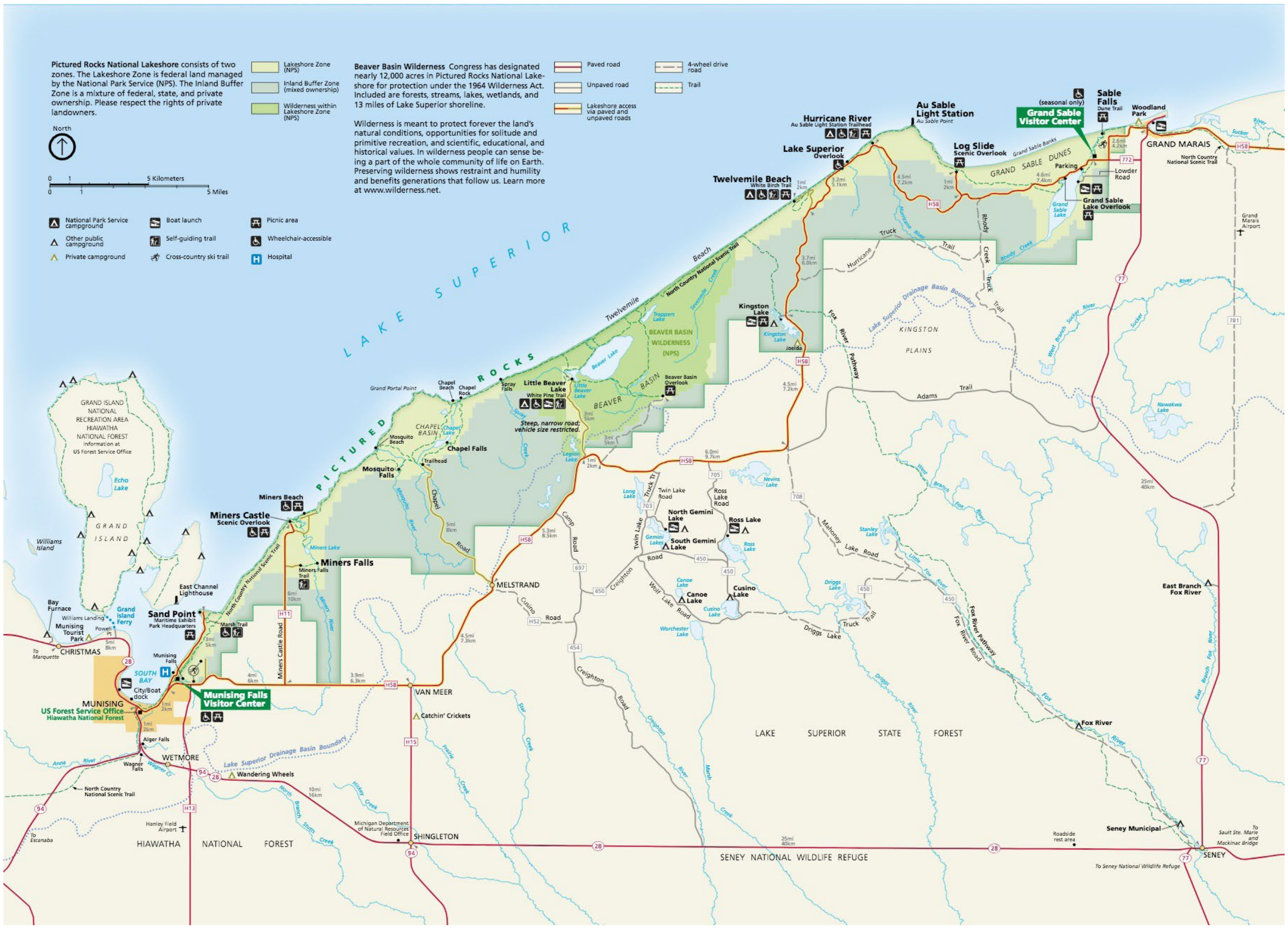


Figure 1. Map of Pictured Rocks National Lakeshore.
The lakeshore hugs the Lake Superior shoreline between Grand Marais (east) and Munising (west). The lakeshore comprises three distinct zones: (1) lakeshore zone belonging to the National Park Service; (2) inland buffer zone of mixed ownership; and (3) wilderness zone within the lakeshore zone. National Park Service map from the Harpers Ferry Center available at https://www.nps.gov/carto (accessed 6 April 2022).

According to the park/lakeshore-purpose statement: "Pictured Rocks National Lakeshore preserves the character, scenic qualities, and natural processes shaping the multi-colored sandstone cliffs, beaches, dunes, wilderness, and forested ecosystems of a distinctive portion of the Lake Superior shoreline. The lakeshore provides for public recreation, inspiration, scientific study, and education about natural and cultural heritage, while still providing for economic utilization of renewable forest resources within an inland buffer zone" (National Park Service 2016, p. 4). Geology features prominently in the lakeshore purpose with direct references to geologic features of the lakeshore.

The lakeshore is divided into separate ownership and management zones: the federally owned shoreline zone directly adjacent to Lake Superior, and the non-federal inland buffer zone (IBZ; darker green area on fig. 1), which preserves the land character and inland lakes as well as protects local watersheds and streams (National Park Service 2019a). The National Park Service does not own or actively manage IBZ land (Laura Waller, Pictured Rocks National Lakeshore, chief of Science and Resource Stewardship, written communication, 9 September 2021). Mechenich et al. (2006) described the lakeshore watersheds in detail. Certain land uses such as sustained-yield timber harvesting and approved recreational activities are permitted within the IBZ, which includes both national and state forest land (Thornberry-Ehrlich 2010; National Park Service 2016). The IBZ at the lakeshore is unique in the National Park System because of the way it is managed (National Park Service 2019a).

The shoreline of Lake Superior is 183 m (602 ft) above sea level. The Pictured Rocks cliffs rise about 60 m (200 ft) above the lake. In addition to the interesting bedrock exposures along the lakeshore, the shoreline also includes 13 km^2 (5 mi^2) of pristine sand dunes, and 19 km (12 mi) of undeveloped sandy beach (National Park Service 2019a). Inland, beyond the shore, glacial landforms have created topography marked by inland kettle lakes as well as hummocky ridges that contain boreal and eastern hardwood forests.

Geologic Setting and History

Michigan consists of 11 physiographic provinces (fig. 2; Schaetzl et al. 2013). Physiography is determined largely by the variations of texture, composition, and structure of the underlying rocks and deposits and how earth surface processes have shaped their characteristic topography. The lakeshore is entirely within the Eastern Upper Peninsula Lowlands province. As described in Schaetzl et al. (2013), delta lowlands, moraine flats, lake plains, swamp, and uplands characterize the province south of Lake Superior. This province is east of the Superior Bedrock Uplands province, characterized by uplands, low ranges, bedrock terrains, and some till plains. The boundary between the two provinces spans the western end of the upper peninsula of Michigan from Lake Michigan north to Lake Superior. The Lake Superior shoreline is but a slice along the edges of the provinces. The steeply rising shores of Lake Superior are testament to its position as a lake set deeply within a highland area (Martin 1916) that is considerably higher than the great lakes to the south—Lake Michigan and Lake Huron.

The geologic setting of Lake Superior and the Pictured Rocks cliffs reflects a long geologic history spanning more than a billion years (table 1). Before 2.5 billion years ago, in the Archean Eon, local granitic crust formed and was metamorphosed in a series of events related to the formation of the North American craton—the ancient stable core of the continent (fig. 3A). From about 1.8 billion to 1.6 billion years ago, in the Paleoproterozoic Era, periodic orogenies (mountain-building events) occurred and modified the craton (Nuhfer and Dalles 2004). Today, the metamorphosed rocks of the craton are buried beneath the sedimentary rocks that compose the Pictured Rocks. Their ancient topography controlled the thickness of overlying younger sediments; these sediments would become the rocks exposed in the lakeshore today. For example, 1.6 billion–1.0 billion years ago, in the Mesoproterozoic Era, sedimentary units accumulated around an Archean regional high—referred to as "White's Ridge"—beneath the Bayfield Peninsula area of Lake Superior (Cannon et al. 1999). The sediments thickened away from the ridge. During this time, the proto–North American landmass called "Laurentia" was part of the supercontinent Rodinia, which included most of the continental crust in existence at the time.

The ages of the geologic units within the lakeshore are from opposite ends of the geologic time scale (table 1 and fig. 4). The older units include the ancient bedrock from the Mesoproterozoic (geologic map unit **Yj**) and early Paleozoic Eras (geologic map units **Cm**, **Ct**, **Oat**, and **Obr**). The younger units include the much more recent Pleistocene and Holocene surficial units ("**Q**" geologic map units), some of which are still forming.

The oldest bedrock exposed in the lakeshore, the Jacobsville Sandstone (**Yj**), is part of the Keweenawan Supergroup—rocks that formed as part of the Midcontinent Rift System. The Mesoproterozoic Midcontinent Rift System is one of Earth's continental rifts, as opposed to mid-ocean rifts; continental rifts form when continental masses break apart (Hinze et al. 1997). The Midcontinent Rift System extends more

Figure 2. Map of physiographic provinces of Michigan.
Pictured Rocks National Lakeshore (green star) is located within the Eastern Upper Peninsula Lowlands province, which dominates the eastern half of the upper peninsula of Michigan. Glacial deposits, boggy plains, and rolling uplands characterize this province. To the west is the Superior Bedrock Uplands province. Great Lakes border the Eastern Upper Peninsual Lowlands province to the north (Superior) and the south (Michigan/Huron). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Schaetzl et al. (2013, figure 1). Base map by Tom Patterson (National Park Service) available at http://www.shadedrelief.com/physical/index.html (accessed 6 April 2022).

Table 1. Geologic time scale.

The geologic time scale puts the divisions of geologic time in stratigraphic order, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses and map unit symbols are bold. The ages of the geologic units within the lakeshore are from opposite ends of the geologic time scale from Mesoproterozoic Era to today. Only geologic units mapped within the lakeshore are included on the table. The Quaternary Period and Tertiary time are part of the Cenozoic Era. The Triassic, Jurassic, and Cretaceous Periods are part of the Mesozoic Era. The periods from Cambrian through Permian are part of the Paleozoic Era. Boundary ages are millions of years ago (MYA) and follow the International Commission on Stratigraphy (2022).

Geologic Time Unit	MYA	Geologic Map Units	Geologic Events
Quaternary Period (Q): Holocene (H)	0.0117–today	**Qb**, **Qsw**, **Qdl** deposited and reworked	Human history; shoreline change, continued erosion and stream incision; Lake Superior forms modern shape; shoreline processes
Quaternary Period (Q): Pleistocene Epoch (PE)	2.58–0.0117	**Odr**, **Qe**, **Qpm**, **Qm**, **Qg**, **Qsg**, **Qs**, **Qkt6**, **Qkt5**, **Qkt4**, **Qkt3**, **Qkt2**, **Qkt1**, **Qd**, **Qts** deposited	Ice age glaciations; river courses modified; weathering and incision accelerated
Tertiary (T): Neogene Period (N): Pliocene Epoch (PL)	5.3–2.58	None mapped	Ongoing erosion and weathering
Tertiary (T): Neogene Period (N): Miocene Epoch (MI)	23.0–5.3	None mapped	Ongoing erosion and weathering
Tertiary (T): Paleogene Period (PG): Oligocene Epoch (OL)	33.9–23.0	None mapped	Ongoing erosion and weathering
Tertiary (T): Paleogene Period (PG): Eocene Epoch (E)	56.0–33.9	None mapped	Ongoing erosion and weathering
Tertiary (T): Paleogene Period (PG): Paleocene Epoch (EP): upper Paleocene (EP)	59.2–56.0	None mapped	Ongoing erosion and weathering
Tertiary (T): Paleogene Period (PG): Paleocene Epoch (EP): lower and middle Paleocene (EP)	66.0–59.2	None mapped	Ongoing erosion and weathering
Cretaceous Period (K)	145.0–66.0	None mapped	**Global mass extinction** at end of Cretaceous (dinosaurs extinct)
Jurassic Period (J)	201.3–145.0	None mapped	Ongoing erosion and weathering
Triassic Period (TR)	251.9–201.3	None mapped	**Global mass extinction** at end of Triassic Breakup of Pangaea begins; Atlantic Ocean opened
Permian Period (P)	298.9–251.9	None mapped	**Global mass extinction** at end of Permian. Supercontinent Pangaea intact.
Pennsylvanian Period (PN)	323.2–298.9	None mapped	Alleghany (Appalachian) Orogeny
Mississippian Period (M)	358.9–323.2	None mapped	Erosion and weathering of overlying sediments
Devonian Period (D)	419.2–358.9	None mapped	**Global mass extinction** near the end of Devonian
Silurian Period (S)	443.8–419.2	None mapped	Ongoing marine sedimentation Neoacadian Orogeny

Table 1, continued. Geologic time scale.

Geologic Time Unit	MYA	Geologic Map Units	Geologic Events
Ordovician Period (O)	485.4–443.8	**Oat**, **Obr** deposited	**Global mass extinction** at end of Ordovician; deeper marine settings Sea level fluctuations; marine and nearshore settings Taconic Orogeny; open marine settings
Cambrian Period (C)	538.8–485.4	**Cm**, **Ct** deposited	Extensive oceans covered most of proto-North America (Laurentia); erosion and weathering
Proterozoic Eon: Neoproterozoic (Z)	1,000–538.8	None mapped	Supercontinent Rodinia rifted apart; erosion and uplift; Lake Superior basin coalesces; rifting ends; basin subsides
Proterozoic Eon: Mesoproterozoic (Y)	1,600–1,000	None mapped	Formation of early supercontinent; Grenville Orogeny; Midcontinent rift began to open; Lake Superior basin developed
Proterozoic Eon: Paleoproterozoic (X)	2,500–1,600	None mapped	Uplift, volcanism, widespread erosion
Archean Eon	~4,000–2,500	None mapped	Oldest known Earth rocks
Hadean Eon	4,600–4,000	None mapped	Formation of Earth approximately 4,600 million years ago

than 2,500 km (1,500 mi) from Kansas in a northeasterly arc through the Lake Superior region and down into southern Michigan (fig. 5). Approximately 1.1 billion years ago, in a setting analogous to today's East African Rift, the crystalline Archean craton of the North American continent began to split in response to a rising mantle plume (body of molten rock). Over tens of millions of years, from about 1.1 billion (fig. 6A; see also fig. 3B) to 1.05 billion years ago, the Midcontinent Rift System developed as the crust thinned and the rocks of the Keweenawan Supergroup formed (Hinze et al. 1997; Ojakangas et al. 1997).

Initial rifting involved fracturing of Earth's crust, which led to eruptions of lava (forming volcanic rocks) and intrusions of plutons (forming plutonic rocks) along the rift. Lava flowed from vents along the center of the rift, which spread laterally toward the rift margins. The earliest lavas (about 1.109 billion years old) are basalts of the Powder Mill Volcanic Group in Wisconsin and Michigan. Later basalts of the Bergland Group include the Chengwatana Volcanics in Wisconsin and the Portage Lake Volcanics in Michigan (fig. 6B; see also fig. 3C; Hinze et al. 1997; Cannon et al. 1999). The Portage Lake Volcanics, famous for their native copper deposits, are flood basalts that erupted rapidly between 1.096 billion and 1.094 billion years ago (fig. 6D; Davis and Paces 1990; Cannon et al. 1999). During intermittent periods of volcanic quiescence, conglomerate and sandstone (sedimentary rocks) were deposited between the lava flows.

Volcanism ceased during the next phase of rift development, following the eruption of the Lake Shore Traps (flood basalts interbedded with coarse-grained conglomerates; "traps" comes from the Swedish word for steps, relating to their stair-step appearance in outcrop) approximately 1.086 billion years ago (Cannon and Nicholson 1992; Ojakangas et al. 1997; Cannon et al. 1999). Down-dropping (sagging) along rift-bounding normal faults (see fig. 3B) developed a major graben (structural basin) in the Lake Superior region (fig. 7). Volcanic rocks on the flanks of the rift eroded, supplying sediments deposited as conglomerate and sandstone (Cannon et al. 1999; Nuhfer and Dalles 2004; Ojakangas et al. 2011). Older, granitic rock on the rift flanks also supplied sediment to the basin as sagging continued because of thermal subsidence and the weight of accumulating sediments. Streams carried these sediments northward and eastward, away from the high relief rift flanks. During this time at the lakeshore, the Jacobsville Sandstone (**Yj**) accumulated in lake, river, and possibly alluvial fan settings. It probably formed after volcanism associated with active rifting had ceased

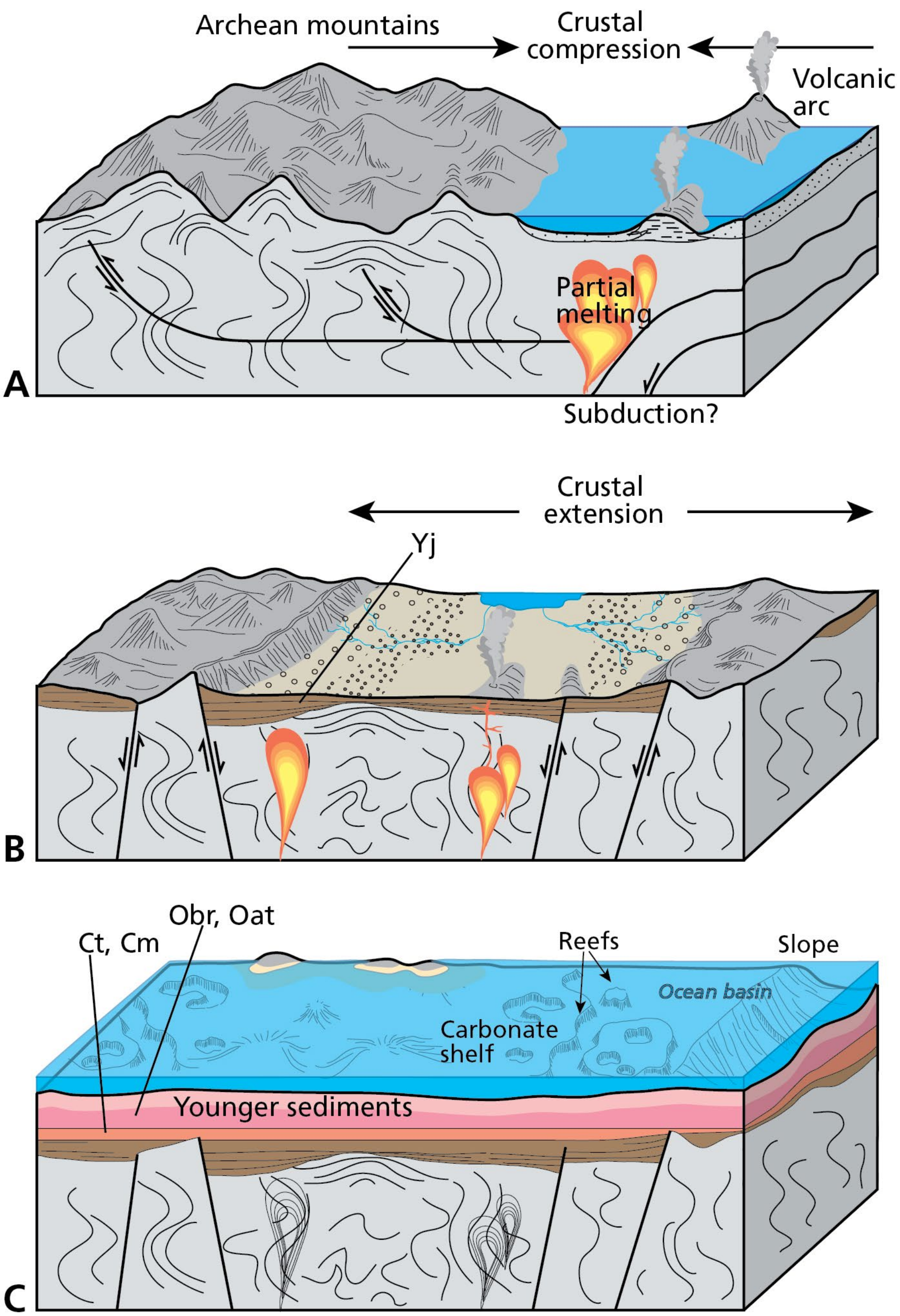


Figure 3. Illustration of the evolution of the landscape and geologic foundation of Pictured Rocks National Lakeshore, 2.5 billion to 444 million years ago.
(A) 2.5 billion to 1.6 billion years ago the North American craton formed in a series of igneous and metamorphic events. These rocks are buried deep beneath the surface of Pictured Rocks National Lakeshore. (B) 1.14 billion to 1.0 billion years ago, crustal extension formed a rift in the North American craton that never fully opened and was buried. The Keweenawan Supergroup of layered volcanics and clastics (fragments of preexisting rocks) was deposited in the rift valley. (C) 540 million to 444 million years ago, intermittent marine basins covered the area collecting thick layers of mixed sediment throughout the early Paleozoic Era. Graphics are not to scale. Colors are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps and correspond to the colors on the geologic time scale (table 1). Map symbols are included for the geologic map units mapped in the GRI GIS data. For more recent landscape evolution, see figure 9. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with information from GRI GIS source data.

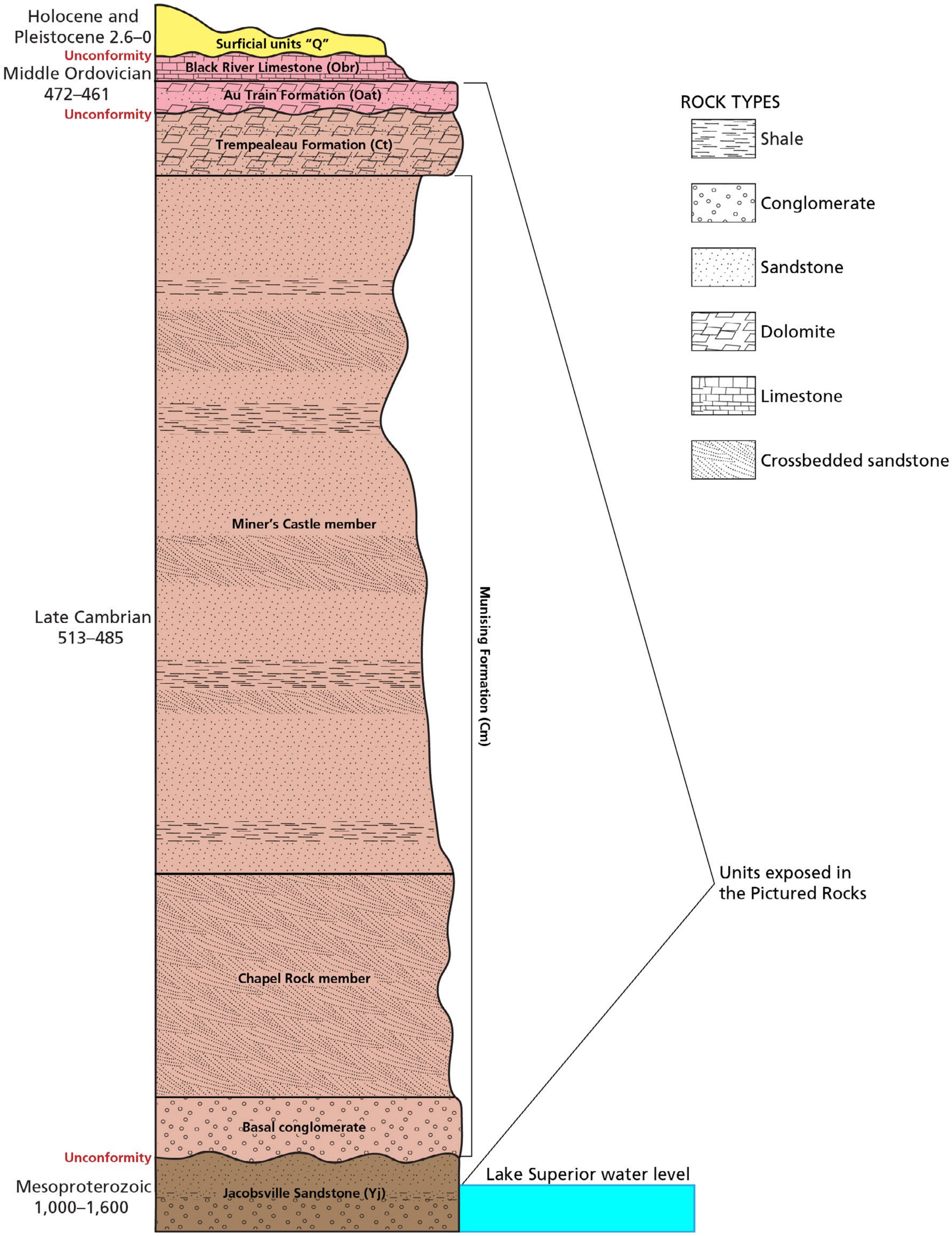


Figure 4. Stratigraphic column for rocks mapped within Pictured Rocks National Lakeshore. Units on the bottom (brown colored Yj) are older than the ascending units represented by a peach color (Cm and Ct) for Cambrian rocks and a pink color (Oat and Obr) for Ordovician rocks. Youngest of all are the unconsolidated surficial deposits, represented by yellow. The GRI GIS data include the Trempealeau Formation (Ct) above the Munising Formation (Cm); however, review of fossil evidence and research of other sources do not support the presence of the Trempealeau Formation in the lakeshore area. Its dolomitic sandstone composition and position capping the Miners Castle Member, point to the lower Au Train Formation (Oat). Colors are standard US Geological Survey colors for geologic time periods. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using GRI GIS source data.

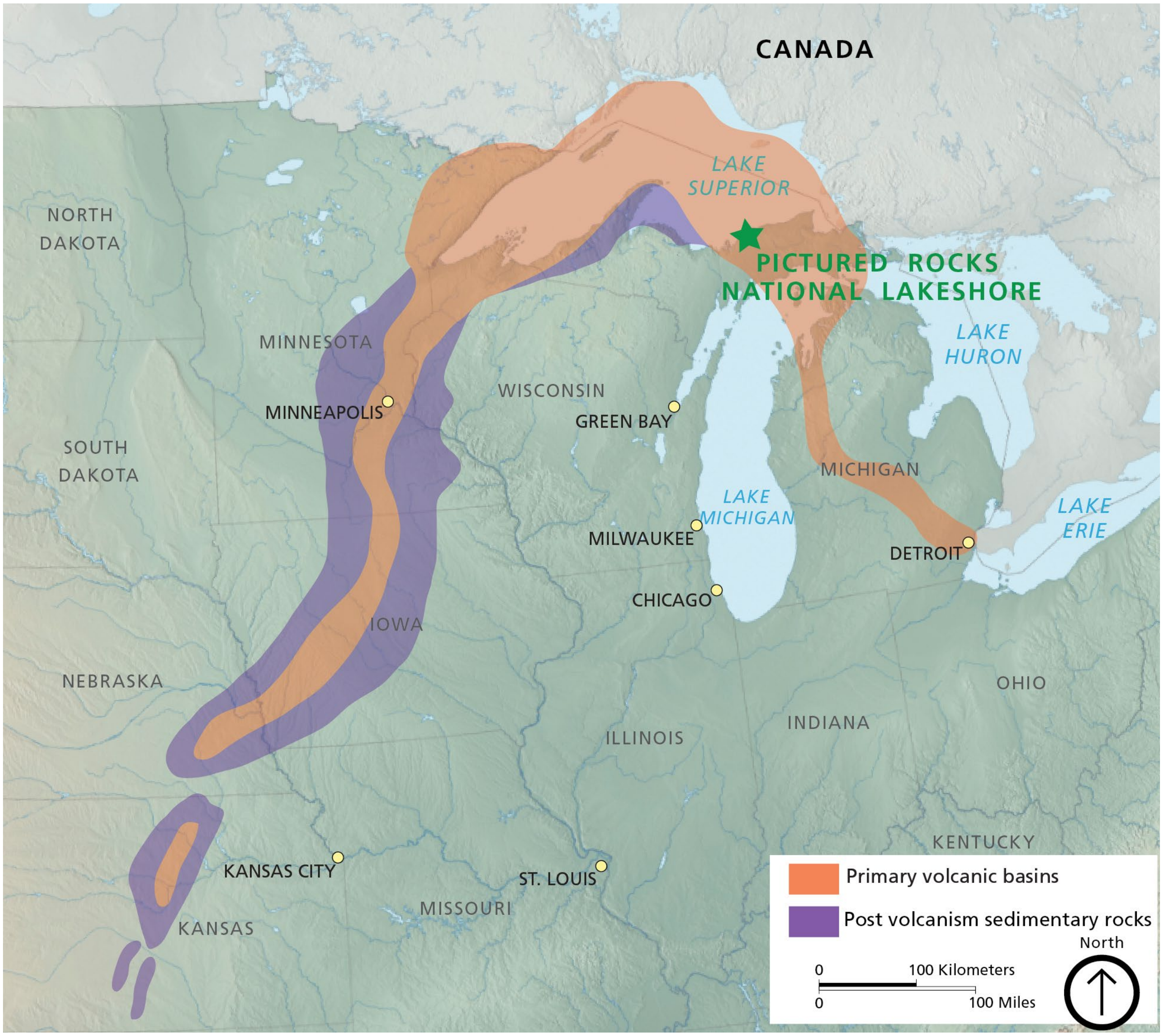
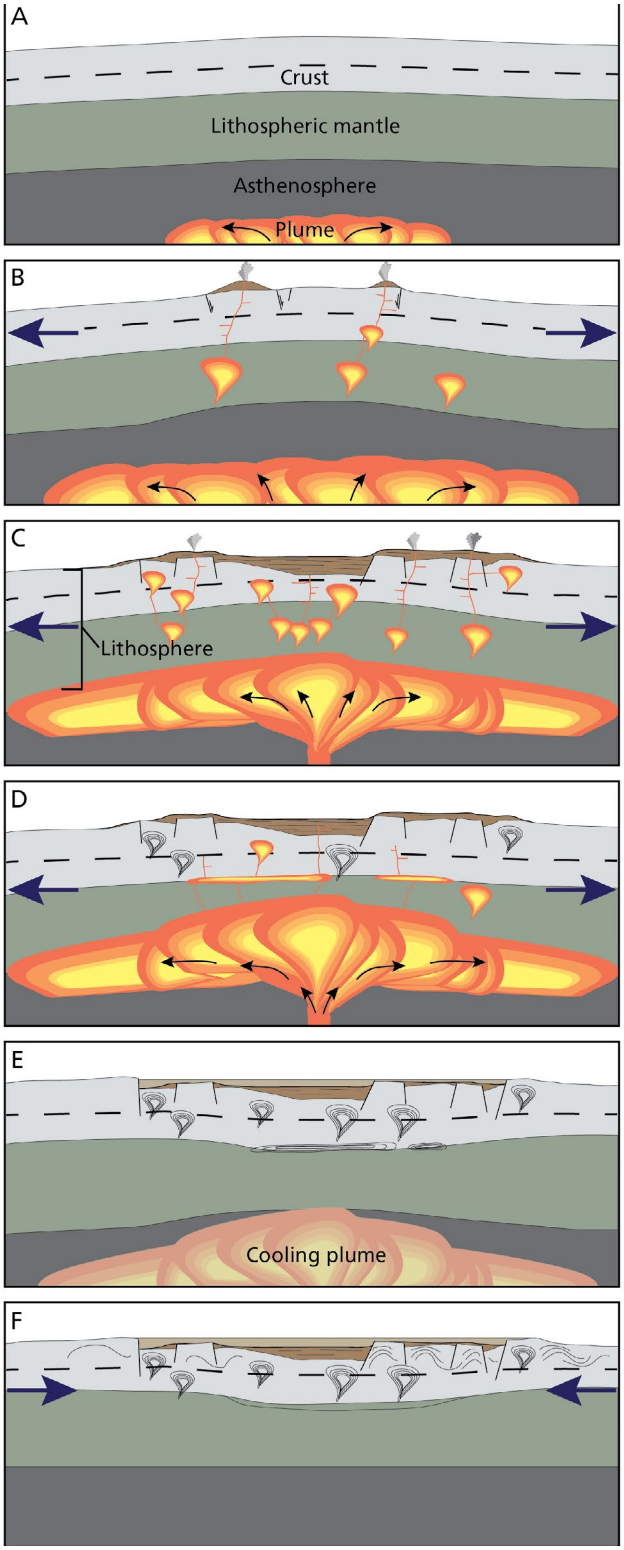


Figure 5. Map of the Midcontinent Rift System.
Orange areas delineate the primary volcanic basins with associated sedimentary and plutonic rocks. The purple areas represent primarily late-stage sedimentary rocks deposited after volcanism had ceased. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Hinze et al. (1997, figure 3). Shaded-relief base map by Tom Patterson (National Park Service) available at http://www.shadedrelief.com/physical/index.html (accessed 6 April 2022).

because it contains clasts of rhyolite and Portage Lake Volcanics (Hamblin 1958; Bornhorst and Rose 1994; Kessler 2019; Kevin Kincare, US Geological Survey, geologist, conference call, 29 July 2020).

Collectively, the 31-km (19-mi) thick accumulated volcanic, plutonic (large bodies of igneous rock formed beneath Earth's surface), and sedimentary rocks filling the rift compose the Keweenawan Supergroup (Behrendt et al. 1988; Cannon et al. 1999; Thornberry-Ehrlich 2015; Richard Ojakangas, University of Minnesota Duluth, geologist, written communication, 12 January 2015). The supergroup rocks were buried by younger Paleozoic rocks, which prevented supergroup rocks from being worn away in the millions of years since their deposition. They are now exposed at the surface only in the Lake Superior region because of long-term erosion removing the Paleozoic cover. Along the southern shore of Lake Superior, rocks of the Keweenawan Supergroup have been tilted to the



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

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.

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.

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.

1.080 billion years ago: The cooling plume dragged the attached lithosphere downward. The added weight of lavas and sediments contributed to sagging. The Jacbobsville Sandstone and other sediments was deposited in the rift.

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.

Figure 6. Evolution of the Midcontinent Rift System.
The rift developed in a series of events: A–F. Large arrows indicate the tectonic stress direction (e.g., extension or compression). The lithosphere and asthenosphere refer to layers in Earth’s crust with the lithosphere being the solid outer crust and uppermost layer of the mantle. The asthenosphere lies beneath the lithosphere and its material yields readily to persistent stresses in a “plastic” way. Schematic graphics are not to scale and represent a generalized cross section through the rift. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Hinze et al. (1997, figure 19).

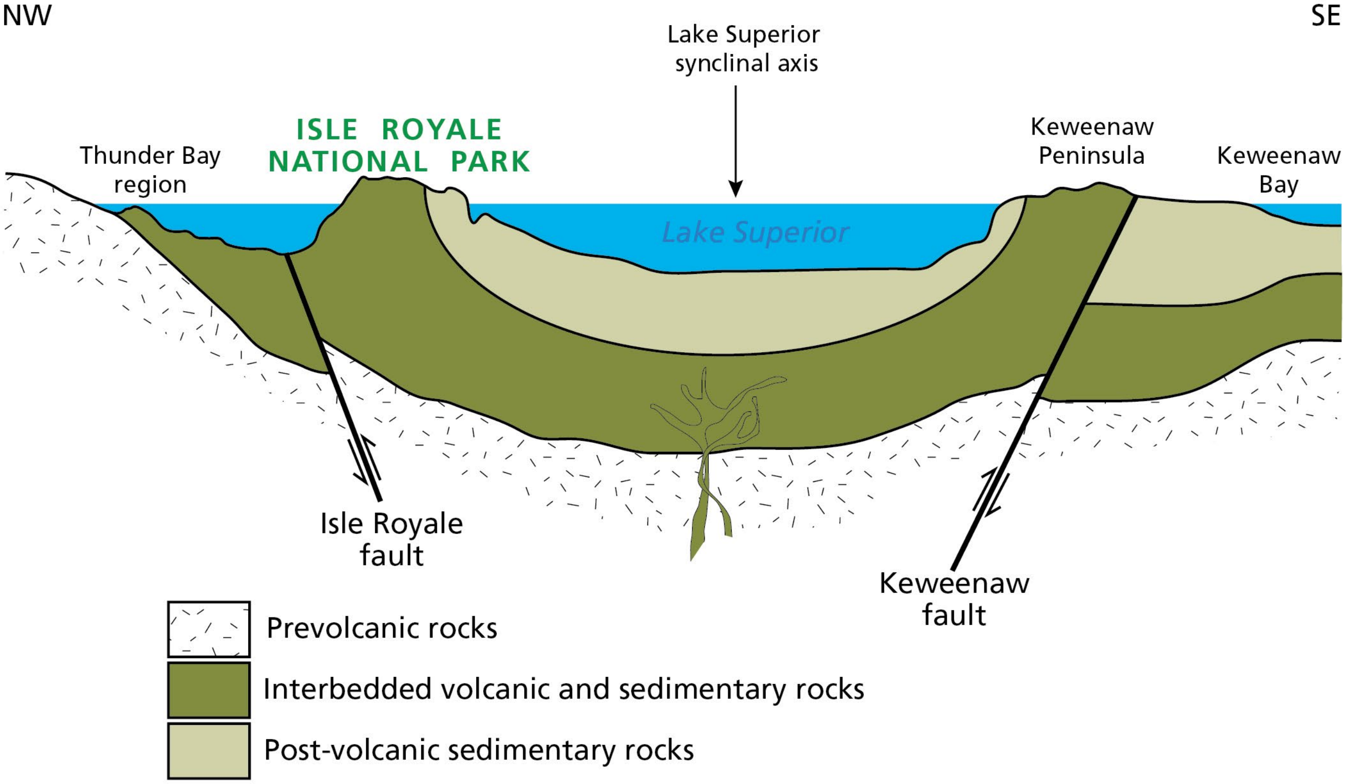


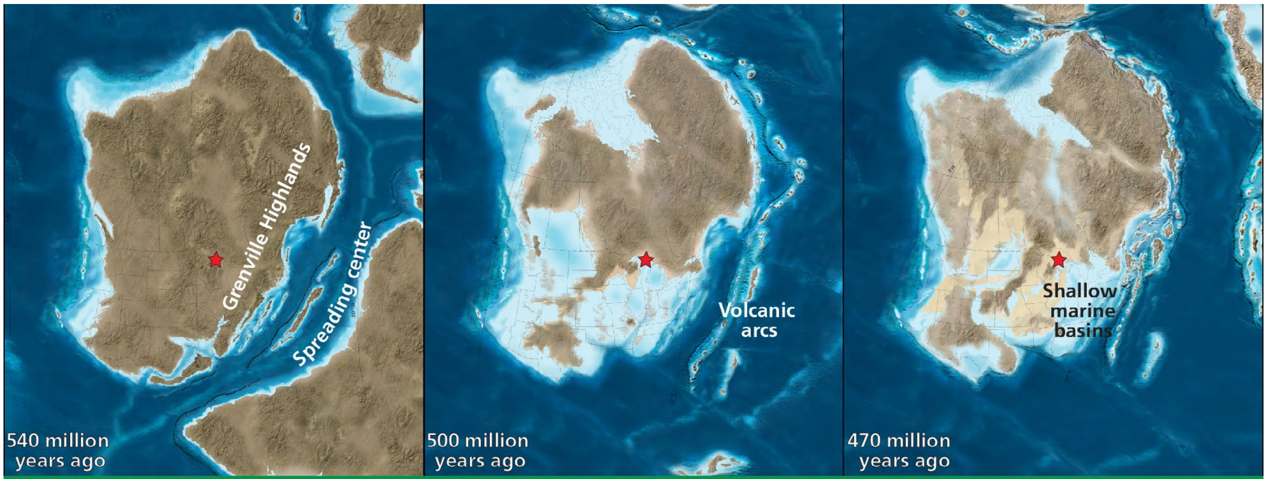
Figure 7. Cross-sectional diagram of the Lake Superior basin.
During development of the Midcontinent Rift System, sagging along rift–bounding normal faults, called the Isle Royale and Keweenaw faults, caused a major graben (basin) in the Lake Superior region to form. Volcanic rocks on the flanks of the rift and older, granitic rock on the rift flanks eroded and supplied sediments to the basin. The basin continued to sag due to thermal subsidence and the weight of the accumulating sediments. Today, Lake Superior occupies a basin bounded by faults with layered rocks tilted towards the Lake Superior synclinal axis, which is a line from which the rock layers slope upward in opposite directions, to form a valley. Pictured Rocks National Lakeshore is located east of this section with post-volcanic sedimentary rocks exposed. Diagram is not to scale. Graphic adapted from Huber (1973) by Trista L. Thornberry-Ehrlich (Colorado State University).

north, forming the Montreal River monocline (bend in rock strata) exposed near the border between northern Wisconsin and Michigan (Cannon et al. 1999).

By the beginning of the Paleozoic Era, approximately 538 million years ago, the area was tectonically passive. Intermittent marine and nearshore conditions (fig. 8; see also fig. 4C) led to the deposition of a mix of limestone, sandstone, conglomerate, dolomite, glauconite, and chert (table 2) of the Munising Formation, Trempealeau Formation, Au Train Formation, and Black River Limestone (geologic map units **Cm**, **Ct**, **Oat**, and **Obr**, respectively)—among the oldest, bottommost layers of the Michigan basin, which is centered on the lower peninsula of Michigan (Hussey 1952; Milstein 1987; Joel 2016). These younger deposits covered the rift rocks and were possibly buried by younger rocks that have since eroded away. The GRI GIS data include the Trempealeau Formation (**Ct**) above the Munising Formation (**Cm**); however, review of fossil evidence and research of other sources preclude the presence of a Trempealeau Formation in the Pictured Rocks National Lakeshore area (Justin Tweet, National Park Service, paleontologist, written communication, 28 July 2020).

About 480 million years ago—after millions of years of tectonic stability—tectonic unrest commenced along the eastern margin of North America. A series of landmass collisions and orogenies throughout the remainder of the Paleozoic Era built the Appalachian Mountains and culminated in the formation of another supercontinent—Pangea (fig. 8). At this time, the Pictured Rocks remained buried under thick piles of Paleozoic sediment in northern Michigan (fig. 9A).

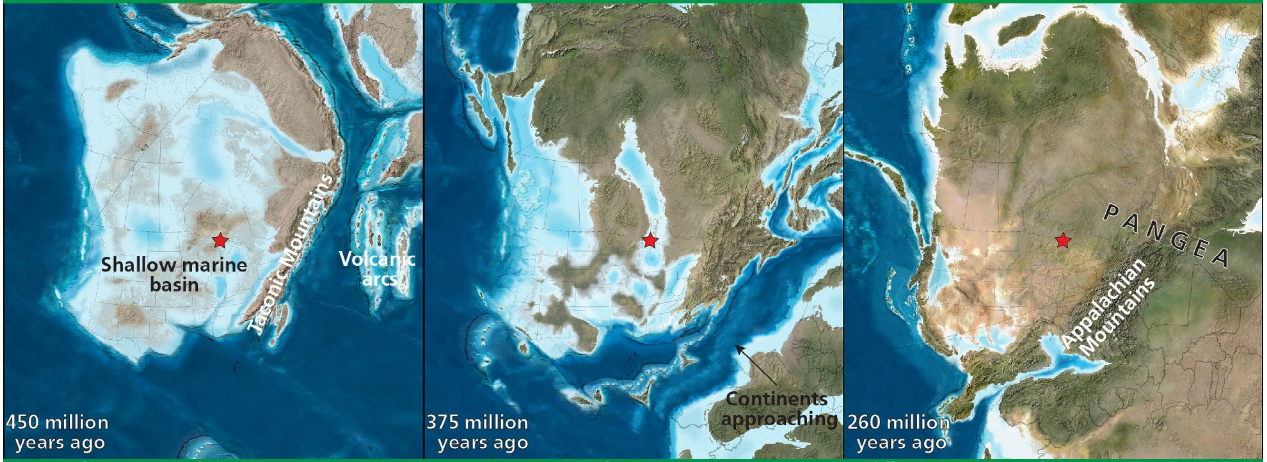
During the Triassic Period of the Mesozoic Era, approximately 250 million years ago, the supercontinent Pangea began to rift apart forming normal, fault-



Early Cambrian Epoch
Eastern edge of early North America was accumulating sediments in a shallow marine setting. Grenville highlands were eroding.

Late Cambrian Epoch
Volcanic arcs and crustal fragments were approaching the eastern margin of North America; longstanding marine settings.

Middle Ordovician Epoch
Intermittent collisions continued. Shallow seas and occasional emergences prevailed in the Lake Superior region.



Late Ordovician Epoch
Volcanic arcs and crustal fragments collided with the eastern margin of North America; mountains rose and rocks metamorphosed.

Late Devonian Epoch
Continents and crustal fragments continued to collide, building higher mountains and a seaward expansion of North America.

Middle Permian Period
Continental collision formed the Appalachian Mountains and assembled the supercontinent, Pangea; weathering continued.

Early Cretaceous Epoch
Pangea continued to rift apart opening the Atlantic Ocean. Weathering and erosion continued. Coastal plain built eastward.

Pleistocene Epoch
Glacial ice locked away vast quantities of water and global sea level was lower; weathering and river incision accelerated.

Holocene Epoch
Weathering and erosion continued; lakeshore processes. The Lake Superior region rebounded isostatically from the lack of heavy ice sheets.

Figure 8. Paleogeographic maps of North America.
The red star indicates the approximate location of Pictured Rocks National Lakeshore. Graphic complied by Trista L. Thornberry-Ehrlich (Colorado State University). Base paleogeographic maps created by Ron Blakey and used under license (North American Key Time Slices © 2013 Colorado Plateau Geosystems Inc.), additional information is available at https://deeptimemaps.com/.

Table 2. Sedimentary rock classification and characteristics.

*Claystones and siltstones can also be called "mudstone," or if they break into thin layers, "shale."
**Carbonate classification is based on Dunham's textural classification scheme (Dunham 1962).

Sedimentary Rock Type	Rock Name	Texture and Process of Formation	Pictured Rocks National Lakeshore geologic map unit examples
Inorganic clastic	Conglomerate (rounded clasts) and Breccia (angular clasts)	Cementation of clasts >2 mm (0.08 in) in size. Higher energy environment (e.g. rivers).	Conglomerate: Layers in **Yj** Breccia: none identified in mapping
	Sandstone	Cementation of clasts 1/16–2 mm (0.0025–0.08 in) in size.	Layers in **Yj**, **Cm**, and **Ct**
	Siltstone*	Cementation of clasts 1/256–1/16 mm (0.00015–0.0025 in) in size.	Layers in **Cm**
	Claystone*	Cementation of clasts <1/256 mm (0.00015 in) in size. Lower energy environment (e.g. floodplains).	Layers in **Yj** and **Cm**
Carbonate clastic**	Fossiliferous Limestone	Generic name for carbonate rock containing fossils.	Layers in **Obr**
	Boundstone	Fossils, fossil fragments, or carbonate mud fragments cemented together during deposition (e. g. reefs).	None identified in mapping
	Grainstone	Grain (e.g., fossil fragments) supported with no carbonate mud. High energy environment. Components cemented together following deposition.	None identified in mapping
	Packstone	Grain (e.g., fossil fragments) supported with some carbonate mud. Lower energy than grainstone. Components cemented together following deposition.	None identified in mapping
	Wackestone	Carbonate mud supported with more than 10% grains and less than 90% carbonate mud. Lower energy than packstone. Components cemented together following deposition.	None identified in mapping
	Mudstone*	Carbonate mud supported with less than 10% grains and more than 90% carbonate mud. Lower energy than wackestone. Components cemented together following deposition.	Layers in **Yj** and **Cm**
Chemical**	Limestone (Carbonate Mud)	Generic name. Formed by the precipitation of calcium (Ca) and carbonate (CO_3^{2-}) ions from water (e. g. lakes or marine environments).	Layers in **Obr**
	Travertine	Precipitation of calcium (Ca) and carbonate (CO_3^{2-}) ions from freshwater (e. g. terrestrial springs).	None identified in mapping
	Dolomite	Precipitation of calcium (Ca), magnesium (Mg), and carbonate (CO_3^{2-}) ions from water. Direct precipitation in shallow marine environments or post-depositional alteration by Mg-rich groundwater.	Layers in **Ct** and **Oat**
	Chert	Dissolution of siliceous marine skeletons (e.g. sponge spicules) followed by precipitation of microcrystalline silica. Biochemical chert typically forms from marine invertebrates.	None identified in mapping
	Evaporites (i.e., gypsum)	Precipitation of salts to form evaporite minerals. Typical of hot, dry environments.	None identified in mapping
	Oolite	Precipitation of calcium carbonate in thin spherical layers around an original particle (e.g., fossil fragment) that is rolled back and forth by tides or waves. Typical of warm, shallow marine environments.	None identified in mapping
Organic	Coal	Peat (partly decomposed plant matter) is buried, heated, and altered over time. Typical of lagoon, swamp, and marsh environments.	None identified in mapping

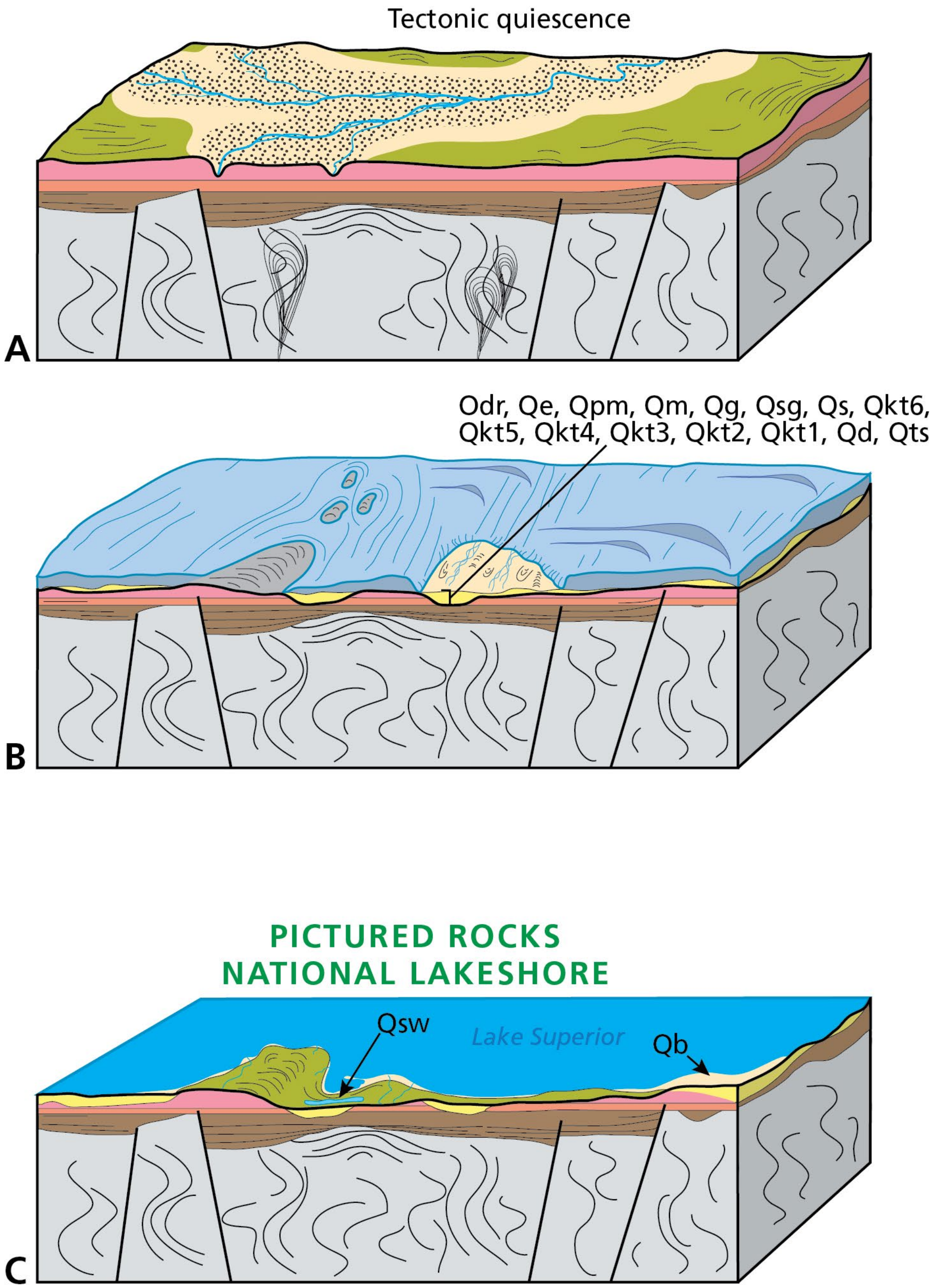


Figure 9. Illustration of the evolution of the landscape and geologic foundation of Pictured Rocks National Lakeshore, 444 million to present.
(A) 444 million to 66 million years ago, deposition of younger sediments buried the Mesoproterozoic and early Paleozoic rocks. Local streams and rivers eroded deeply into the overlying sediments. (B) 66 million to 10,000 years ago, erosion and weathering exposed the resistant clastic rocks of the lakeshore area. Glaciers scoured the Lake Superior landscape several times and left thick deposits of till and outwash inland. (C) At present, Lake Superior fills the basin scoured by the glaciers. The Pictured Rocks remain as bedrock remnants. Lake levels fluctuate causing changes in the morphology of the young surficial deposits at the shoreline. Graphics are not to scale. Colors are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps and correspond to the colors on the geologic time scale (table 1). Map symbols are included for the geologic map units mapped in the GRI GIS data. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with information from GRI GIS source data.

bounded rift basins along the eastern coast of North America. Unlike the Mesoproterozoic Midcontinent Rift System, this rifting resulted in the development of an ocean (Atlantic Ocean) and led to the configuration of continents that persists today (Cenozoic Era). The effects of these events did not reach northern Michigan. A rock record from the Mesozoic and early Cenozoic Eras does not exist in this part of Michigan. Whatever rocks were deposited atop today's exposed bedrock were stripped away by erosion and weathering over millennia.

The Midcontinent Rift System remained buried for hundreds of millions of years until the Pleistocene Epoch (2.6 million–11,700 years ago; see fig. 8) when glaciers—an agent of profound landscape change—scoured and sculpted the Lake Superior basin. As described in the "Glacial Features" section, during the Pleistocene Epoch, global climate shifts brought alternating cold periods—ice ages or glacials—and relatively warm periods or interglacials (similar to modern climate). Continental ice sheets descended south from the Arctic, extensively reshaping the landscape of the lakeshore and Lake Superior (figs. 9B and 10). Huge glaciers of the Laurentide ice sheet intermittently advanced and retreated through the Great Lakes region. Successive glacials tend to obliterate or obscure evidence of former glacials. Glaciers scoured vast basins and channels into the bedrock (e.g., glacial drainage channels carved into sandstones of the Munising Formation, **Cm**) leaving "islands" between them. The glaciers and associated meltwater deposited vast amount of glacial drift or mixed glacial sediments across the region, including stacked push moraines (surficial geologic map unit **Qpm**), outwash and outwash fans (**Qsg**, **Qg**, **Qm**), kame terraces (**Qkt1–6**), diamicton ridges (**Qd**), and thin sediment over bedrock (**Qts**; VanderMeer et al. 2020). Additionally, glacial processes constructed distinctive landforms such as drumlins (**Qdr**), eskers (**Qe**), and meltwater sluiceways (**Qs**) (VanderMeer et al. 2020). Today's landscape is primarily a reflection of the most recent glaciation (Robert Young, Western Carolina University, geologist, written communication, 26 January 2022). These features are described and defined in the "Glacial Features" section.

As climate warmed in the late Pleistocene–early Holocene Epochs, glaciers melted and retreated from south to north. Incredible volumes of meltwater were released. The southern edge of the retreating ice sheet barricaded local streams, which formerly flowed north, and water ponded up until it reached a level that permitted flow through a southerly outlet in the ice. The namesakes of the glacial lakes (e.g., Lake Nemadji, Lake Algonquin, Lake Minong, Lake Brule, Lake Ashland, and Lake Ontonagon) are the modern basins in which these lakes stood. The glacial lakes along the southern edge of the retreating ice eventually coalesced to form the Great Lakes (Clayton 1984).

For Lake Superior, remnants of these glacial lakes include elevated shorelines, in places 150 m (500 ft) above the modern shoreline. At Apostle Islands National Lakeshore, west of Pictured Rocks National Lakeshore, the Nipissing phase shoreline is preserved at approximately 12 m (40 ft) higher than the current level of Lake Superior (VanderMeer et al. 2020). During the height of the Nipissing phase about 5,000 calendar years before present (cal yr BP), the water surface was about 3 m (10 ft) above current lake level, and it covered the area now occupied by Lake Huron (Larson and Schaetzl, 2001; VanderMeer et al. 2020). At this time, its outlet (Port Huron) was cut downward, and the level of Lake Superior fell until about 2,200–2,100 years ago when water dropped below the elevation of Sault Sainte Marie, effectively creating two separate basins—Lake Superior and Lake Huron. This occurred because of uneven postglacial isostatic uplift of the Saint Marys River outlet at Sault Sainte Marie to Lake Superior. When the weight of the glaciers was gone, the Saint Marys River uplifted more than the surrounding basin, making it the place where the basins were separated upon water levels lowering (Hansel et al. 1985; Bona 1990; Larsen 1999). Lake Superior and the other Great Lakes assumed their present configuration by about 2,000 years ago when the lakes began to drain into the Atlantic Ocean via the Saint Lawrence River (LaBerge 1994; Busch 2008).

Throughout the Holocene Epoch, 11,700 years ago to today, earth surface processes have continued to weather and rework preexisting material on the landscape (see fig. 9C). Peat and muck (**Qp**) are accumulating in isolated, poorly drained areas; depressions; and river floodplains (VanderMeer et al. 2020). Beach sand (**Qb**) is continually washing up and being reworked along the Lake Superior shoreline forming dunes and beach ridges (VanderMeer et al. 2020). Fluctuating lake levels are important drivers of coastal processes, influence the location of coastal features, and affect the supply of sediment to the shore and nearshore zones (Robert Young, Western Carolina University, geologist, written communication, 26 January 2022). Since humans have inhabited the lakeshore landscape, they have disturbed areas large enough to be mapped as disturbed land, gravel and/or sand pits (**Qdl**; VanderMeer et al. 2020).

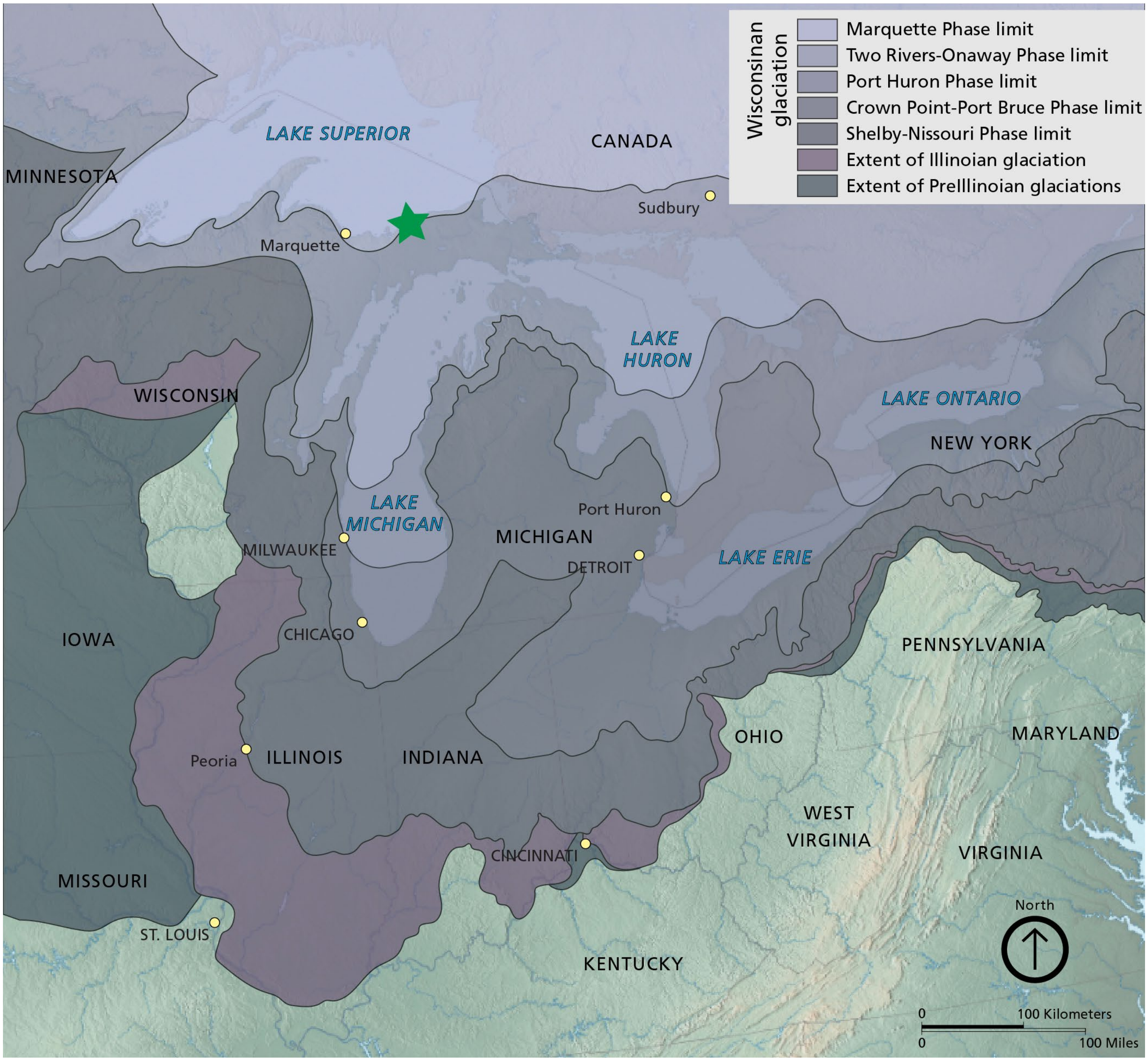


Figure 10. Glaciations in the Great Lakes region.
Glacial ice advanced and retreated many times over the landscape. Each advance obscured or obliterated evidence of previous advances, thus the record is best for the most recent major glaciation—the Wisconsinan (lightest purple on graphic). Green star depicts the location of the lakeshore. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Larson (2011). Shaded-relief base map by Tom Patterson (National Park Service) available at http://www.shadedrelief.com/physical/index.html (accessed 11 April 2022).

Geologic Significance and Connections

Geologic themes are among the significance statements and fundamental resources and values expressed in the lakeshore's foundation document (National Park Service 2016) and include the following: (1) the picturesque landscape sculpted by impressive geologic processes, forming the Pictured Rocks cliffs, perched Grand Sable Dunes, 19-km (12-mi) of pristine beach, and cascading waterfalls; (2) pristine dune ecosystem; (3) mining history; (4) geomorphic processes and associated features such as high sandstone bluffs, sea caves, hanging waterfalls, sand dunes, sand banks, kettle lakes, arches, and pocket lakes; and (5) water resources such as streams, rivers, lakes, ponds, fens, bogs, wet meadows, and waterfalls.

Land use is another important resource and value at the lakeshore (fig. 11; National Park Service 2016). Whether drawn to the lakeshore's natural beauty, because of spiritual and/or cultural traditions, or for purely economic (e.g., resource extraction) reasons, the geologic resources and features of the area fundamentally influenced the traditional, historic, and continuing uses of the land.

Following the retreat of the glaciers by 11,700 years ago, vegetation became established and woodland conditions developed in the area. Evidence of the earliest known inhabitants of the shores of Lake Superior, or *Gichigami* as it is called by the Anishinaabe (the so-called Ojibwe), is from the Archaic Period (8,000 to 1,000 BCE [before common era]; Justice 2006). American Indians (*Note*: This is the term used in National Park Service 2016) were able to find food, red clay for pottery, and stone-tool material, including quartzite (a hard granular rock composed of quartz minerals that originated as sandstone but was compacted and recrystallized during metamorphism) and native copper that were mined in the Lake Superior region, for example, at Isle Royale and the Keweenaw Peninsula (Jordahl 1994; Busch 2008). The copper had been deposited in rift-related volcanic rocks (see "Geologic Setting and History" section) by circulation of mineral-laden geothermal fluids (Stein et al. 2015). Flint projectile points discovered in Grand Sable Dunes are also from the Archaic Period. Other functional objects discovered at the lakeshore include stone flakes, fire-cracked rock, intact hearths, and lithic-reduction areas (using quartzite cobbles) possibly dating into the Early/Initial Woodland Period (Legg and Anderton 2010), which covers about 1,000 to 200 BCE (Justice 2006). Beaches were likely sites for fishing camps and supplying local raw materials (Legg and Anderton 2010).

Managers consider the lakeshore to be only about 7% inventoried for archeological sites, with 75 recorded sites, including some along the shores of inland lakes (National Park Service 2016). Additional archeological sites are probably located near former shorelines. Modeling ancient shorelines using previous higher lake levels (e.g., Nipissing) may help to reveal these locations (Legg and Anderton 2010). An Anishinaabe village was located on Grand Island (not within the lakeshore) and burial sites are known within the boundary of the lakeshore (Mechenich et al. 2006).

Fur traders entered the area in the early 1600s and used the natural harbors and bays for trading points. Once the fur trade declined, the logging industry took over, changing the forests and landscapes of the southern shore of Lake Superior. Logging camps

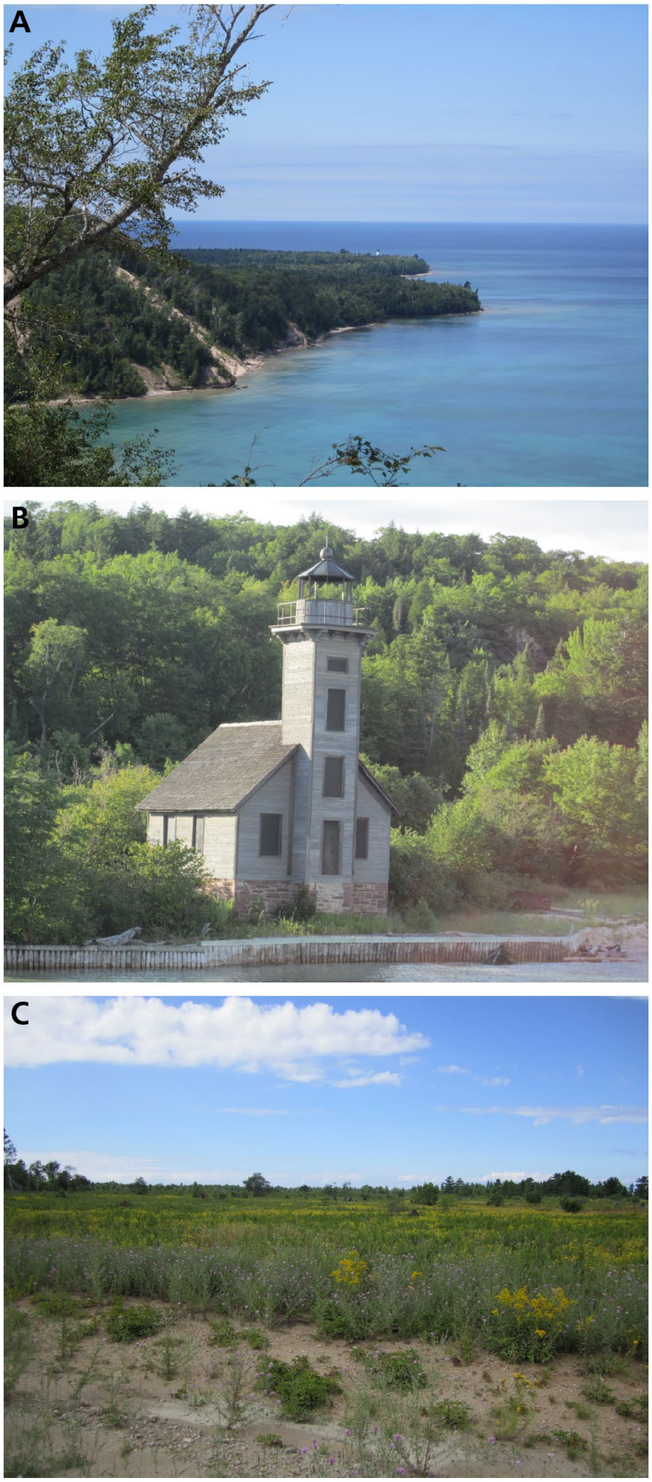


Figure 11. Photographs of cultural features at Pictured Rocks National Lakeshore.
(A) View looking westward from Log Slide overlook towards Au Sable light station. (B) Grand Island East Channel lighthouse. (C) Open area, burned as prescribed, left bare of trees as a legacy of logging activities in the lakeshore. Photographs by Trista L. Thornberry-Ehrlich (Colorado State University) taken in summer 2009.

dotted the lakeshore landscape and local streams were harnessed to transport logs from the uplands to Lake Superior (National Park Service 2016). Logging impacted stream channels by destabilizing their banks and loading their channels with eroded sediments (Mechenich et al. 2006). Mining also happened at the lakeshore (see "Disturbed Lands" section). Interest in mining was due to potential sources of sand for glass of the auto industry (GRI conference call participants, conference call, 27 July 2020). The lakeshore protects evidence of historic land use, such as those related to iron processing (furnace/smelter ruins and charcoal kilns), logging (logging railroads, roads, and camps), and development of recreational camps for hunting and fishing, as well as small farming operations, including orchards, fallow farm fields, and a historic barn (National Park Service 2016).

The lakeshore has a rich maritime history starting at least with canoe travel associated with the fur trade and continuing to the present day. Geology strongly influenced maritime history both by posing a hazard (i.e., dangerous rocky shoals and reefs and shallow offshore sand bars) and a solution. At least 21 shipwrecks are known offshore from Pictured Rocks National Lakeshore (National Park Service 2020a). The bedrock cliffs at the lakeshore were perfect perches for lighthouses to guide ships to mainland harbors and away from rocky shoals and running aground. The lakeshore has a collection of maritime historic resources, including Munising Range lights and the Au Sable Light Station, as well as the Grand Marais Harbor of Refuge and the Sand Point Life Saving Station—two former US Coast Guard stations (Mechenich et al. 2006; National Park Service 2016). Shipwrecks submerged on the lakebed belong to the State of Michigan but are cared for jointly with the National Park Service (National Park Service 2016; Bruce Leutscher, Pictured Rocks National Lakeshore, chief of Science and Resource Stewardship, conference call, 29 July 2020).

Pictured Rocks Ecosystem

Because of its great size, Lake Superior creates a maritime climate in an otherwise northern, continental setting. Inherent in this maritime climate are cool summers and warm winters compared to adjacent northern, continental areas. The lakeshore is in the transition zone between these climates. Here, boreal forest and northern hardwood forest meet with interspersed wetlands and streams. The ecosystems in this zone offer myriad habitats that support robust wildlife populations (National Park Service 2016). Notable among the fauna and flora living at the lakeshore are many high trophic-level predators (peregrine falcons, merlin, red-shouldered hawks, fishers, martens, bears, and wolves) and more than 200 bird species, as well as a diverse forest understory scattered with an assemblage of orchids that receive much of their moisture from the dense cloud banks drifting inland from Lake Superior (National Park Service 2016). Grand Sable Dunes contains the richest orchid assemblage in the Great Lakes region (National Park Service 2019b).

Habitats in the lakeshore harbor rare plant species. One such plant, the endangered Pitchers thistle (*Cirsium pitcheri*) takes 10 years to mature and produce seeds. Pitchers thistle is native only to the Great Lakes region (Lakes Superior and Michigan) and requires a sandy substrate (surficial geologic map unit **Qb**) available at the lakeshore; the other known population on Lake Superior is at Sault Sainte Marie. Several rare plant species grow at the springs along the base of the Grand Sable banks, which alone is home to 10 species on Michigan's lists of endangered species or species of concern (Mechenich et al. 2006). Large bogs and marshes (**Qp**) occur at Sand Point, northeast of Beaver Lake, around Legion Lake, Miners Lake, Little Chapel Lake, and east of Twelvemile Beach campground. These are typically filled-in lacustrine depressions with a sphagnum base and support orchids (Mechenich et al. 2006). Vernal pools (see "Inland Lacustrine and Wetland Features and Processes" section) provide critical habitat for amphibians, invertebrates (e.g., fairy shrimp), and some mammals (Mechenich et al. 2006). Pine islands (pockets of forest) inhabit old dune ridges and provide habitat diversity in the dunes (Thornberry-Ehrlich 2010).

Mechenich et al. (2006) provided mapped percentages of land use and vegetative cover for the lakeshore. Michigan State University maintains a natural feature inventory for the state, including detailed information about natural communities at https://mnfi.anr.msu.edu/services/natural-features-inventory. Additional information about other natural resources is available from the following sources.

- Soil Resources Inventory product: https://irma.nps.gov/Datastore/Reference/Profile/1048957
- Vegetation mapping inventory: https://irma.nps.gov/Datastore/Reference/Profile/2233355
- Historical and projected climate change trends: https://irma.nps.gov/Datastore/Reference/Profile/2266988
- Landscape disturbance data: https://irma.nps.gov/Datastore/Reference/Profile/2217357
- Aquatic studies to determine information needs https://irma.nps.gov/DataStore/Reference/Profile/593327

- Climate change summary: https://irma.nps.gov/DataStore/Reference/Profile/2224671
- Future warming and visitation: https://irma.nps.gov/DataStore/Reference/Profile/2222696
- Stressors and threats to Great Lakes waters: https://irma.nps.gov/DataStore/Reference/Profile/2165239
- NPS Water Resources Division, information regarding the lakeshore's water resources: http://go.nps.gov/waterresources
- NPS Great Lakes Network, inventories and monitoring information about natural resources such as climate and weather, bats, amphibians, contaminants, diatoms, land birds, landscape dynamics, vegetation, water quality (lakes), and water quality (rivers): https://www.nps.gov/im/glkn/index.htm

Geologic Features, Processes, and Issues

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

Geologic resources, including the sea bluffs, high cliffs, sea caves, wave-cut benches, sand dunes, kettle lakes, and beaches at the lakeshore are fundamental to its history and modern preservation and interpretation (Thornberry-Ehrlich 2010). Geologic processes, forming regionally and nationally rare features, are listed in the lakeshore's significance statements (National Park Service 2016). Specifically identified were the Pictured Rocks cliffs, the perched Grand Sable Dunes, Twelvemile Beach, and many cascading waterfalls. During the 2010 scoping meeting, geologic mapping, and 2020 conference call, participants (see "Acknowledgments" section) identified the following features, processes, and resource management issues. Relevant geologic map units (referenced using map unit symbols) are associated with the following features, processes, and resource management issues, listed roughly in order of significance, but also with features and processes listed before issues. Table 3 describes the geologic map units in the GRI GIS data and identifies the geologic features, processes, and resource management issues associated with each. Resources, references, and suggestions for park managers follows.

- Pictured Rocks
- Sedimentary Rock Features
- Lake Superior Shoreline
- Surficial Deposits
- Aeolian Features and Processes
- Fluvial Features and Processes
- Inland Lacustrine and Wetland Features and Processes
- Glacial Features
- Geologic Hazards
- Climate Change
- Disturbed Lands
- Paleontological Resources Inventory, Monitoring, and Protection

The lakeshore is a natural classroom providing visitors the opportunity to learn about geologic features and processes, geologic history, glaciations, and landscape evolution. For example, Stein et al. (2015) provided a view of how Lake Superior parks, including Pictured Rocks National Lakeshore, are useful to explain the Midcontinent Rift System and the concept of rifting in general. In particular, the rocks of the Jacobsville Sandstone (geologic map unit **Yj**) represent sediments deposited immediately after the rifting. Geologists are studying these rocks to learn when and how rift volcanism ended.

Table 3. Geologic features, processes, and resource management issues associated with geologic map units in Pictured Rocks National Lakeshore.

Detailed descriptions of each map unit are in the ancillary map information document (piro_geology.pdf), which is included in the GRI GIS data.

Note: The GRI GIS data include the Trempealeau Formation (Ct) above the Munising Formation (Cm); however, review of fossil evidence and research of other sources preclude the presence of a Trempealeau Formation in the Pictured Rocks National Lakeshore area (Justin Tweet, National Park Service, paleontologist, written communication, 28 July 2020). The GRI map team is investigating the possibility of updating bedrock mapping with a more accurate and detailed source scale and correcting these geologic map unit discrepancies. This report reflects the existing GRI GIS data while identifying the need for more accurate source map information.

Map Unit (symbol)	Description and Spatial Distribution	Features, Processes, and Potential Resource Management Issues
Disturbed land, gravel and/or sand pit (**Qdl**)	**Qdl** occurs in three locations mapped as active or recently active sand and gravel pits (mapped as "pit" in VanderMeer et al. 2020). It composes less than 1% of the mapped surficial units within the lakeshore boundary.	**Disturbed Lands** **Qdl** is disturbed land. No mitigation is planned but monitoring both road works and quarrying by other landowners is important.

Table 3, continued. Geologic features, processes, and resource management issues associated with geologic map units in Pictured Rocks National Lakeshore.

Map Unit (symbol)	Description and Spatial Distribution	Features, Processes, and Potential Resource Management Issues
Beach sand (**Qb**)	**Qb** is mapped over 25 areas within the lakeshore boundary, composing about 6% of the lakeshore area. **Qb** is buff or tan, well-sorted fine to medium quartz (common colorless mineral containing silicon dioxide) sand. Some accumulation of gravel and cobbles occur locally.	**Lake Superior Shoreline** Beach sand is accumulating and being reworked along the present shorelines of Lake Superior. **Aeolian Features and Processes** **Qb** includes dunes and beach ridges. **Paleontological Resources Inventory, Monitoring, and Protection** Reworked horn corals have washed up on beaches.
Peat and muck (**Qp**)	**Qp** composes about 19% of the mapped area within the lakeshore boundary spread among 303 polygons. **Qp** refers to isolated, poorly drained areas, commonly depressions or near rivers.	**Inland Lacustrine and Wetland Features and Processes** **Qp** accumulates is boggy areas or wetlands. Paleontological Resources Inventory, Monitoring, and Protection **Qp** may contain fossil pollen spores for a paleoclimatic record.
Thin sediment above bedrock (**Qts**)	**Qts** includes undifferentiated glacial and/or post-glacial sediments less than about 5 m (16 ft) thick above bedrock. **Qts** covers about 23% of the mapped area within the lakeshore boundary spread across 104 distinct polygons.	**Disturbed Lands** Areas of **Qdl** occur within **Qts** because **Qts** contains an abundance of sorted sand and gravel.
Diamicton ridge (**Qd**)	**Qd** was mapped as 30 separate polygon areas and covers less than 1% of the lakeshore area. **Qd** appears in thin, discontinuous linear ridges of unsorted rocks with a range of particle sizes. Silt and clay form a matrix around granite (coarse grained igneous rock) and sandstone gravel, cobbles, and/or boulders.	**Glacial Features** **Qd** formed as northeast–southwest oriented ridges along former glacial ice margin positions where the glacier stagnated momentarily. At these locations, the glacial ice deposited a vast amount of sediment.
Kame terrace 1–6 (**Qkt1–6**)	**Qkt1–6** covers vast areas within the lakeshore boundary; the cumulative amount is about 36% of the area with 130 mapped polygons. These six units consist of bedded fine to coarse, quartz-rich outwash sand. Their numbers refer to their elevation in a series of flat, step-like surfaces north of the crest of the Grand Marais and Munising outwash fans (**Qg** and **Qm**). **Qkt1** is highest at 270–285 m (885–935 ft) above sea level. **Qkt2** is at 255–265 m (835–870 ft). **Qkt3** is at 240–250 m (785–820 ft). **Qkt4** is at 220–235 m (720–770 ft). **Qkt5** is at 205–215 m (670–705 ft). **Qkt6** is at 190–200 m (625–655 ft). Glacial deposits such as **Qkt1–6** are part of an important and productive regional aquifer.	**Glacial Features** Kame terraces form along waters flowing from the melting glacial ice. They typically have smooth topography with interspersed areas of kettle depressions. At the lakeshore, all the surfaces slope gently eastward and formed as meltwater was routed that direction between the former glacial ice margin to the north and the crests (heads of outwash) of the fans to the south (**Qg** and **Qm**). **Disturbed Lands** Areas of **Qdl** occur within **Qtk1** and **Qkt4** because of these terraces' abundant, sorted sand and gravel.
Meltwater sluiceway (**Qs**)	**Qs** occurs as three mapped polygons in the lakeshore boundary and covers less than 1% of the total area. The edges of **Qs** are also a line feature in the GRI GIS data showing channel margins. **Qs** is bedded fine to coarse, quartz-rich outwash sand concentrated in channels that are oriented roughly north–south. Gravel and cobbles are also present.	**Glacial Features** Channels of **Qs** cut across **Qg** and **Qm** fans as a result of excess meltwater spilling southward from the former glacial margin during glacial retreat northwards.
Outwash, undifferentiated (**Qsg**)	**Qsg** encompasses about 7% of the mapped area within the lakeshore boundary with 98 polygons. A bedded sand matrix surrounds granite and sandstone gravel and/or cobbles. **Qsg** is not associated with **Qg** or **Qm**.	**Glacial Features** **Qsg** was deposited as the glacier melted away. A hummocky surface resulted from sediment collapsing into melting of former (buried) isolated ice blocks.

Table 3, continued. Geologic features, processes, and resource management issues associated with geologic map units in Pictured Rocks National Lakeshore.

Map Unit (symbol)	Description and Spatial Distribution	Features, Processes, and Potential Resource Management Issues
Grand Marais outwash fan complex (**Qg**)	**Qg** covers about 3% of the area within the lakeshore boundary. This is spread over five polygons. **Qg** is similar in composition and form to **Qsg** and **Qm**; however, it splays out in a series of fans that gently slope southward from the crest (head of outwash deposit) that denotes the former glacial ice margin position. It is lower in elevation than **Qm**.	**Glacial Features** **Qg** is also referred to as the "Grand Marais moraine." **Qg** reflects a prolonged period of outwash deposition that stemmed from a narrow source area. The southern extent of **Qg** is obscured.
Munising outwash fan complex (**Qm**)	**Qm** is mapped in four polygons and covers less than 1% of the land area within the lakeshore boundary. **Qm** is similar in composition and form to **Qsg** and **Qg**; however, it splays out in a series of fans that gently slope southward from the crest (head of outwash deposit) that denotes and former glacial ice margin position. It is higher in elevation than **Qg**.	**Glacial Features** **Qm** is also referred to as the "Munising moraine." **Qm** reflects a prolonged period of outwash deposition that stemmed from a narrow source area. **Qm** fans have a clear terminus to the south.
Push moraine (**Qpm**)	**Qpm** is not mapped within the lakeshore boundary.	**Glacial Features** As the name suggests, **Qpm** forms as a glacier readvances and pushes older sediment into mounds.
Esker (**Qe**)	**Qe** occurs as 15 mapped polygons within the lakeshore boundary and covers less than 1% of the total area. The flow directions of **Qe** are also a line feature in the GRI GIS data showing which way the glacial stream flowed. **Qe** exists locally as isolated sinuous ridges of stratified fine to coarse sand and scant gravel.	**Glacial Features** Eskers form as subglacial or ice-walled meltwater tunnels perpendicular to the ice margin, depositing, sorting, and reworking sediments along its course. Most **Qe** ridges are oriented northwest–southeast.
Drumlin (**Qdr**)	**Qdr** is not mapped within the lakeshore boundary. Four polygons of **Qdr** are beyond the lakeshore. Qdr composes isolated elliptical ridges of till (fine sand/clay matrix with granite and sandstone gravel and cobbles).	**Glacial Features** Drumlins form as the glacier passes over glacial till, shaping it into elliptical masses whose long axes indicate the direction of glacial movement. At the lakeshore, the drumlins are oriented northwest–southeast.
Neoproterozoic–Early Ordovician bedrock (**OCPRbr**)	**OCPRbr** is the surficial map unit in which all the bedrock exposures are grouped (map unit R in VanderMeer et al. 2020). See "Geologic Map Data" chapter for an explanation of the two GRI GIS data sets. On the geologic map, bedrock exposures include **Oat**, **Ct**, and **Cm**. Some outcrops of **Yj** may also be present. **OCPRbr** is exposed in less than 1% of the mapped area within the lakeshore boundary in 16 locations.	See individual bedrock unit descriptions.
Black River Limestone (**Obr**)	**Obr** is not mapped within the lakeshore boundary but crops out south of the boundary. **Obr** is primarily hard, buff to gray limestone with some argillaceous (clayey) layers and some dolomite with some shaly (laminated rock with mud, clay, or silt) layers present locally. **Obr** is part of a regional aquifer.	**Sedimentary Rock Features** Layers in **Obr** reveal subaerial erosion and disconformity (a break in the sequence of sedimentary layers) with borings of unknown organisms. **Obr** was deposited in shallow water settings close to shore. **Paleontological Resources Inventory, Monitoring, and Protection** **Obr** is very fossiliferous and includes trace fossils.

Table 3, continued. Geologic features, processes, and resource management issues associated with geologic map units in Pictured Rocks National Lakeshore.

Map Unit (symbol)	Description and Spatial Distribution	Features, Processes, and Potential Resource Management Issues
Au Train Formation (**Oat**)	**Oat** underlies about 10% of the area mapped within the lakeshore boundary. **Oat** is primarily medium- to fine-grained dolomitic sandstone. The ratio of sand to dolomite ranges widely with some pure beds of one or the other component. **Oat** forms the uppermost units of the Pictured Rocks between Miners Castle and Sand Point. It is a cap rock of the outermost northern cuesta (a landform with a steep face on one side and a gentle slope on the other) of the ancient Michigan basin. **Oat** is part of a regional aquifer.	**Pictured Rocks** The Miners River flows over **Oat** at Miners Falls. **Geologic Hazards** Exposures of **Oat** along cliff edges are prone to rockfall. **Sedimentary Rock Features** **Oat** contains abundant glauconite (a mineral appearing dull green earthy and rich in iron and potassium) layers which accumulate in moderate to deep water settings that are receiving little sediment from land sources. Glauconite forms by three processes: (1) alteration of the fecal pellets of bottom-dwelling organisms, (2) modification of particles of clays by seawater, and (3) direct precipitation from seawater. **Paleontological Resources Inventory, Monitoring, and Protection** **Oat** is fossiliferous and includes remains of trilobites, ostracoderm fish armor, brachiopods, gastropods, nautiloids, monoplacophorans, chitons, conodonts, and hyoliths.
Trempealeau Formation (**Ct**)	**Ct** is mapped in about 45% of the lakeshore area, covering the most area of any geologic map unit, but actual outcrops are restricted to the top edge of the cliffs in the western half of the lakeshore. It forms a cap rock of buff to brown, dolomitic sandstone. **Ct** is part of a regional aquifer.	**Geologic Hazards** Exposures of **Ct** along cliff edges are prone to rockfall. **Sedimentary Rock Features** Similar to **Oat**, **Ct** contains glauconite, as well as minor amounts of chert, suggesting a depositional setting in deep water.
Munising Formation (**Cm**)	**Cm** is mapped within the lakeshore boundary and underlies about 40% of the lakeshore area. Surficial stains on **Cm** produce the various shades of red, brown, yellow and black in major outcrops. **Cm** includes three distinct units, in ascending order: the basal conglomerate, the Chapel Rock Member, and the Miners Castle Member. The units are not broken out in the GRI GIS data. The basal conglomerate includes vein quartz, quartzite, and chert as large pebbles. It crops out along the base of the Pictured Rocks. The Chapel Rock Member is cross-bedded, quartz-rich sandstone and appears along the entire length of the Pictured Rocks. The Miners Castle Member is poorly sorted, quartz-rich sandstone with some cross-beds and shale layers. It tends to form slopes rather than cliffs and is well exposed at Tahquamenon falls. **Cm** is an important part of a regional aquifer but is not used much because shallower aquifers are available.	**Geologic Hazards** Exposures of Cm make up most of the cliffs that are occasionally spalling off into Lake Superior. **Glacial Features** Melting glaciers created glacial drainage channels in **Cm** about 9,600 years ago. These are visible at Chapel Creek, Mosquito River, and Beaver basin. **Sedimentary Rock Features** The vertical variations of rock features within **Cm** suggest a variety of depositional settings. Conglomerates typically form in high-energy, moving-water environments. The sorted grains and large cross-beds in the middle member suggest wave action (nearshore) or running water deposition (fluvial). The highest layers are more heterogenous with mud cracks, ripple marks, clastic dikes, clay pebbles, and sand concretions suggesting shifting depositional environments from mudflats to flowing water to deeper water settings. **Paleontological Resources Inventory, Monitoring, and Protection** **Cm** is fossiliferous containing conodonts and trace fossils Skolithos and Planolites.
Jacobsville Sandstone (**Yj**)	**Yj** is mapped within the lakeshore boundary. It makes up about 6% of the lakeshore area. It crops out in the northeast part of the lakeshore with good exposures at Au Sable Point and in the bluffs behind Grand Marais. **Yj** is mostly red and reddish-brown, medium- to coarse-grained quartz grains. The base of the unit is mostly coarse conglomerate. Some siltstone and shale layers occur higher in the unit.	**Sedimentary Rock Features** **Yj** was deposited in associating with recent volcanism and rifting. High energy streams deposited coarse conglomerates and occasional incursions of deeper water left shale layers.

Pictured Rocks

Lending their name to the official lakeshore, the dramatic sandstone cliffs, or Pictured Rocks, appear painted because of the colorful stains of mineral precipitates striping their surface. The colors form as groundwater seeps from fissures in the cliff face. The local geochemistry of the water and bedrock create the resulting color: Groundwater percolating through different layers of rock encounters different rock compositions. Minerals are dissolved by groundwater from the bedrock, flow along cracks and bedding planes, and are redeposited as the groundwater emerges at the rock face as a seep. Orange and rusty red colors originate in seeps rich in iron (Fe), green and blue are from copper (Cu), white is from limonite or calcium (Ca), and brown, black to purple is from manganese (Mn) (fig. 12; Thornberry-Ehrlich 2010; Joel 2016).

Because the rocks form a resistant ledge, they are prone to creating waterfalls along the shore. More than 10 waterfalls occur within the lakeshore boundary (fig. 13; National Park Service 2016). The development of the cliffs and other shoreline features is discussed in the "Lake Superior Shoreline" section.

A geologic formation is named for a geographic feature, such as a stream, mountain, 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 a "type section." Type localities and type sections have both scientific and educational significance. Because type localities and type sections commonly occur where a formation was originally described and named, they also may have historical significance. Many of the geologic map-unit names in the GRI GIS data refer to local geographic features, and many are very well exposed at locations in the lakeshore, for example, Miners Castle Member and Chapel Rock (Hamblin 1958). Information about any named geologic unit may be found at the US Geologic Names Lexicon (Geolex), which is a national compilation of formal names and descriptions administered by the US Geological Survey (see "Guidance for Resource Management" chapter).

The bedrock that forms the cliffs at the lakeshore is buried beneath a thick mantle of glacial deposits in other parts of northern Michigan. The oldest bedrock, the Jacobsville Sandstone (geologic map unit **Yj**; type locality near the town of Jacobsville, Michigan, on the Keweenaw Peninsula), crops out along the western side of Grand Island (Reed and Daniels 1987). Here it appears red in color with some white layers and veins caused by the leeching of hematite (an iron-rich mineral) by percolating groundwater. At Grand Marais, the Sable Falls flows over hard, erosion-resistant layers in the Jacobsville Sandstone. The contact between the Jacobsville Sandstone and the overlying Munising Formation is unconformable; it represents a period of erosion or nondeposition—a gap of time in the geologic rock record (Hamblin 1958; Reed and Daniels 1987).

The Cambrian Munising Formation (**Cm**) forms the bulk of the Pictured Rocks outcrops visible along Lake Superior's shoreline. These are among the best exposures of Cambrian rocks in Michigan (Reed and Daniels 1987; Thornberry-Ehrlich 2010). The highest cliffs in the lakeshore form within the Chapel Rock Member of the Munising Formation whose type locality is at Chapel Rock, along the lakeshore. The tall white cliffs are at their highest on the west side of Grand Portal Point. Above the Chapel Rock, the more friable, "punky" sandstone of the Miners Castle Member (named for its type locality) forms many of the distinctive erosional or weathering features at the lakeshore (Hamblin 1958; Reed and Daniels 19897; Thornberry-Ehrlich 2010).

Above the Miners Castle Member is the hard, dolomitic sandstone of the Trempealeau Formation (**Ct**), which is distinctive in that it forms a cap rock and appears along the top edge of the Pictured Rocks cliffs (Milstein 1987). The GRI GIS data include the Trempealeau Formation (**Ct**) above the Munising Formation (**Cm**); however, review of fossil evidence and research of other sources preclude the presence of a Trempealeau Formation in the Pictured Rocks National Lakeshore area (Justin Tweet, National Park Service, paleontologist, written communication, 28 July 2020). Waterfalls such as Bridalveil, Miners, Spray, and Chapel flow over the cap rock in dramatic sprays to the lake below (fig. 13, also see inside cover; National Park Service 2016).

Above an unconformable contact with the Cambrian Munising Formation (**Cm**), the erosion-resistant, dolomitic sandstone of the Ordovician Au Train Formation (**Oat**) also acts as a regional cap rock supporting the formation of cliffs at Pictured Rocks (Hamblin 1958). This is a regional cliff-forming unit that is exposed in a concentric pattern within the Michigan basin, similar to the Silurian rocks that underlie the Niagara Escarpment (Thornberry-Ehrlich 2010). The Au Train Formation is the youngest bedrock within the lakeshore boundary; its type locality is at Au Train Falls, in Alger County in northern Michigan (Hamblin 1958).

Sedimentary Rock Features

Sedimentary rock features may contain clues as to the environmental conditions at the time of deposition. For example, texture (size, shape, and orientation of individual grains) of sedimentary rocks reflects

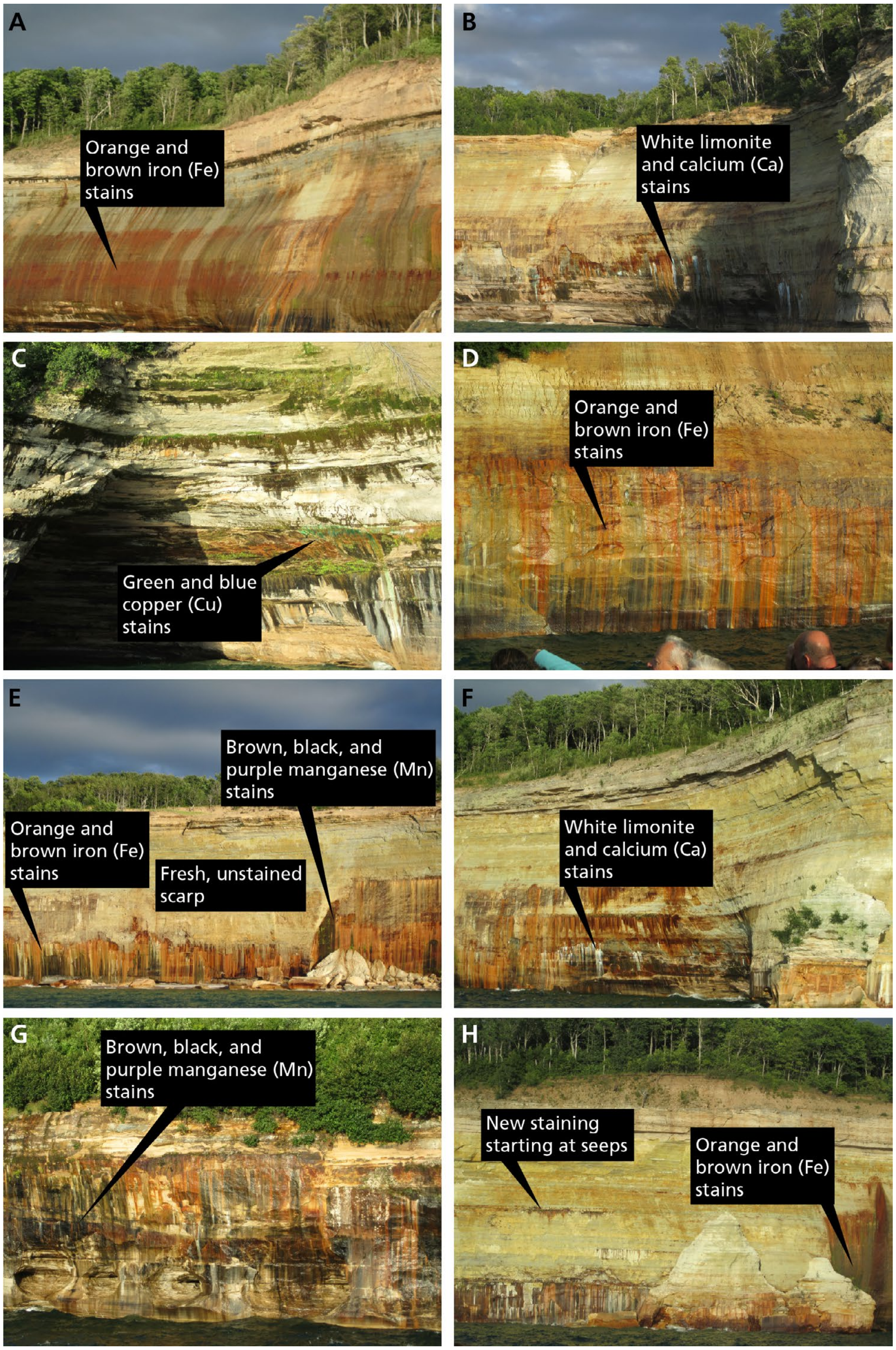


Figure 12. Photographs of the Pictured Rocks cliffs.
Water seeping through the bedrock dissolves minerals, which then precipitate out of solution once the water reaches the cliff surface. The resulting mineral stains make the rocks appear painted. (A) Orange and brown stains come from iron-rich precipitates. (B) White stains come from limonite (formed by weathering of iron-bearing minerals) or calcium stains. (C) Vivid green and blue stains arise from copper minerals. (D) Orange and brown bands streak down the rock face. (E) Brown, black, and purple streaks are from manganese minerals. (F) Various minerals precipitating at one location adds dramatic colored streaks to the rock face. (G) Mineral stains and shoreline erosion features (sea caves) overlap at many locations. (H) Slope movements reveal fresh surfaces that almost immediately begin to stain as seeps reach the new surface. Photographs by Trista L. Thornberry-Ehrlich (Colorado State University) taken in summer 2009.

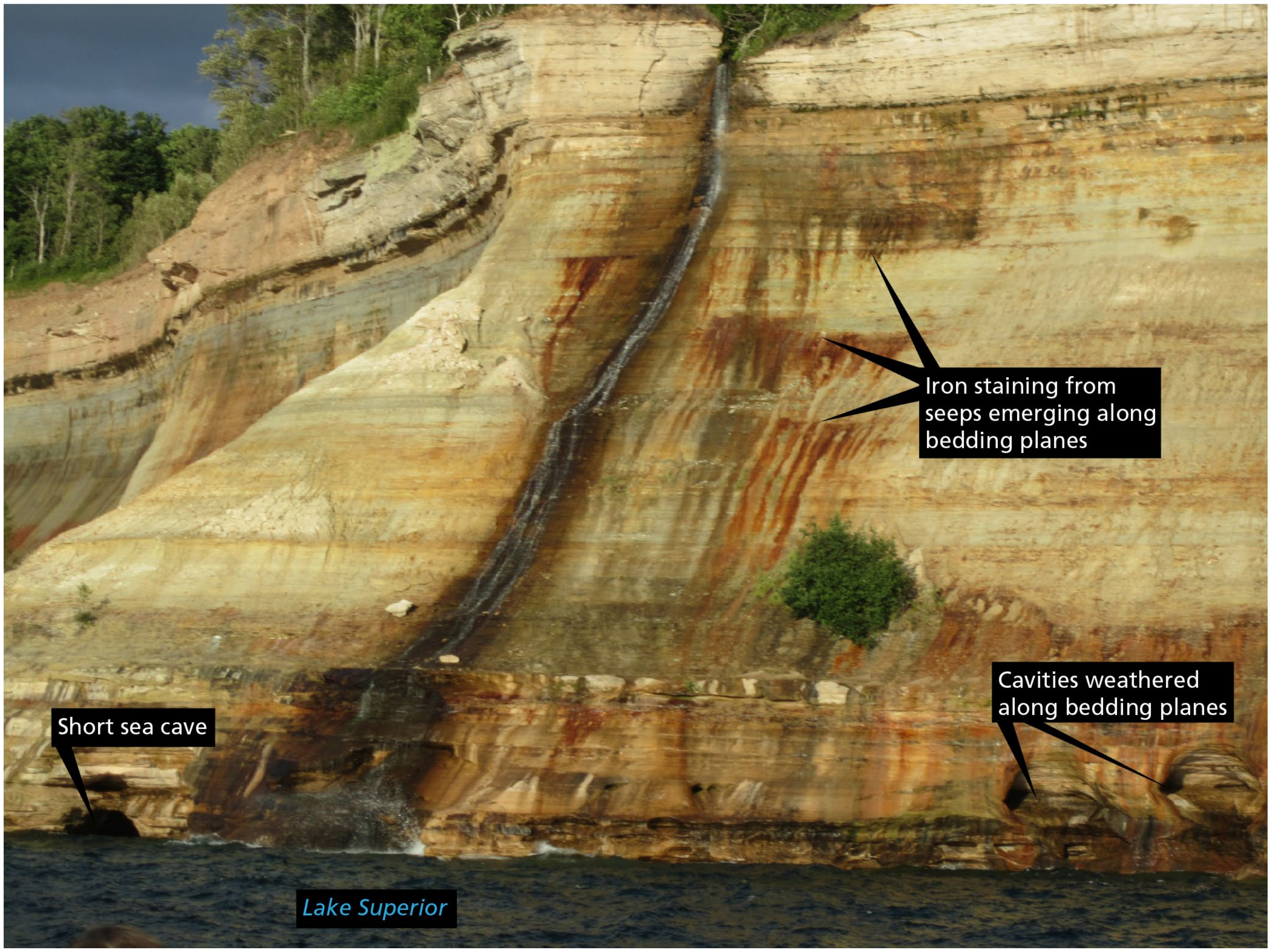


Figure 13. Photograph of Bridalveil Falls.
Waterfalls form along the cliff face where streams flowing from the uplands intersect the precipice. Here, erosion-resistant cap rock overlies weaker, more friable rock creating overhangs and ledges for waterfalls. Other notable features in the photograph include sea caves and cavities weathered along the shoreline as well as orange and brown iron staining emerging from seeps. Photograph by Trista L. Thornberry-Ehrlich (Colorado State University) taken in summer 2009.

the nature of transport and depositional processes. Higher-energy depositional environments, such as fast-moving streams, deposit larger (heavier) clasts while transporting away smaller (lighter) clasts. Where water moves slowly or is stagnant, such as in lakes, the water cannot transport even the smallest clasts and they are deposited (silt and clay). Wind transports and deposits sand-sized or smaller clasts (see table 2). Because some of the ancient bedrock (geologic map units **Yj**, **Cm**, **Ct**, **Oat**, and **Obr**) formed in similar (moving water) environments as the modern shoreline system (surficial geologic map unit **Qb**), the saying “the present is the key to the past” (an adage summarizing uniformitarianism) is truly applicable at the lakeshore (fig. 14).

Sedimentary rock features such as cross-beds are common in the Jacobsville Sandstone and Munising Formation (**Yj** and **Cm**, respectively). Cross-bedding is layering within a sedimentary rock at an angle to the main bedding plane; in outcrop, it appears as roughly horizontal to tilted units composed of inclined layers. Cross-beds form during deposition on the inclined surfaces of bedforms such as ripples and dunes. Cross-beds indicate that the sediments were deposited by a flowing medium, commonly water or wind. Cross-bedding can be used to determine the direction of sand transport or movement in a deposit. Providing an analogy, modern crossbedding is revealed by digging into river sandbars or dune deposits and viewing a cross-sectional profile.

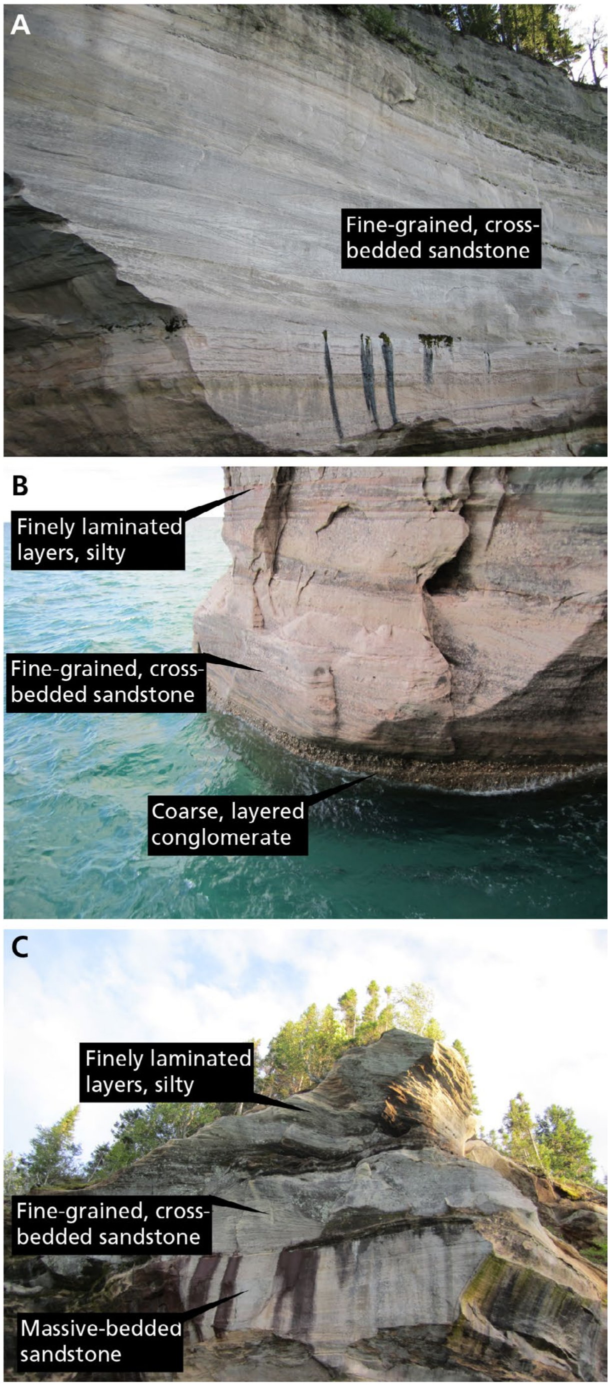


Figure 14. Photographs of sedimentary features within the bedrock.
Ancient depositional environments come to life as features indicative of their settings persist in the exposed rocks at the lakeshore. High energy environments are depicted by layers of coarse-grained conglomerate. Cross-bedded sandstones were deposited in flowing water. Calm water areas were conducive to accumulations of finer sediments. Photographs by Trista L. Thornberry-Ehrlich (Colorado State University) taken in summer 2009.

Other sedimentary features common to the geologic map units of the lakeshore including mud cracks, ripple marks, clastic dikes, clay pebbles, and sand concretions. Mud cracks are sedimentary structures formed as muddy sediment dries and contracts forming interconnected networks of polygons on the surface. The cracks may fill with other sediment. Ripple marks are sedimentary structures (i.e., bedforms of the lower flow regime) and indicate agitation by water (current or waves) or wind. A clastic dike is a seam of sedimentary material that fills an open fracture in and cuts across sedimentary layering in other, adjacent rock types. Clastic dikes form rapidly by fluidized injection or passively by water, wind, and gravity wherein sediment is swept into open cracks. Clay pebbles form when surficial clay is ripped up and tumbled into pebble shapes by moving water or wind. Sand concretions form as a hard, compact mass of matter formed by the precipitation of mineral cement within the spaces between particles and is found in sedimentary rock. Though sometimes irregular masses, concretions are often ovoid or spherical in shape.

In addition to information regarding the original depositional environment, sedimentary rock features may record a regional "view" of the landscape at a particular place in time. A history of debate and improved scientific understanding over the age of the bedrock at the lakeshore is longstanding. Early works lumped all the bedrock at the lakeshore as Cambrian sandstones (Hamblin 1958). Later, the Jacobsville Formation (**Yj**) was reassigned to the latest Precambrian (now referred to as the Neoproterozoic; see table 1) based on a lack of fossils, flow directions recorded in the unit's cross-beds, and an original source area for the sediments that was different from that of the overlying, fossiliferous Munising (**Cm**), Trempealeau (**Ct**), and Au Train (**Oat**) Formations (Reed and Daniels 1987; Thornberry-Ehrlich 2010). Note that the GRI GIS data include the Trempealeau Formation (**Ct**) above the Munising Formation (**Cm**); however, review of fossil evidence and research of other sources preclude the presence of a Trempealeau Formation in the Pictured Rocks National Lakeshore area (Justin Tweet, National Park Service, paleontologist, written communication, 28 July 2020). Initially, geologists thought the mountains of the Keweenaw Peninsula were the source for Jacobsville sediments. Later, examination of cross-bedding within the formation (indicating southwest-flowing transport) revealed the source was actually to the north, in Canada. The northern Michigan highlands were the source of Munising and Trempealeau sediments. The Munising Formation contains north-flowing cross-bed indicators (Milstein 1987; Thornberry-Ehrlich 2010).

Lake Superior Shoreline

The five Great Lakes parks—Apostle Islands National Lakeshore, Grand Portage National Monument, Isle Royale National Park, Pictured Rocks National Lakeshore, and Sleeping Bear Dunes National Lakeshore—have more than 965 km (600 mi) of shoreline combined (Curdts 2011). Pictured Rocks National Lakeshore has approximately 62 km (37 mi) of Lake Superior shoreline and is, therefore, considered coastal and managed accordingly (Curdts 2011). The shoreline is a line or zone that is the intersection of a body of water and land; it migrates with changes of the water level and is part of the coastal environment. The coastal environment is defined broadly as the area lying at the interface between land and sea (or other large body of water). The coast includes a zone of shallow water, where waves are able to transport sediment onto and along a beach. The coastal environment also incorporates areas landward of this shallow water zone, including beaches, cliffs, bluffs, and marshes, that are affected to some degree by the direct or indirect effects of waves and currents, localized weather, perched groundwater forming wetlands, wind and aeolian processes (Robert Young, Western Carolina University, geologist, written communication, 26 January 2022). The coastal environment—characterized by factors such as wave energy, sediment supply, sediment type, slope, width, and past geologic history—may extend inland for a few kilometers/miles (Wyckoff 1999).

Pictured Rocks National Lakeshore is along the southeastern edge of Lake Superior, the second largest freshwater lake (by surface area; 82,100 km^2 [31,700 mi^2]) in the world; it holds 10% of the liquid freshwater on Earth. Even at its great size, Lake Superior is much smaller than an ocean and thus typically has smaller waves and currents; however, these waves can be quite impactful (Engstrom 1985). Lake Superior experiences only minimal astronomical tides, but wind sometimes pushes water up against one shore and it flows back the opposite direction in an event called a seiche. Seiche (“slosh”) waves can reach several meters high and are almost always present in Lake Superior (International Joint Commission 2014). Seiches can cause freak waves that surprise kayakers, as well as stir up the water column, releasing nutrients or, potentially, contaminants from different water levels and/or bottom sediments (International Joint Commission 2014). They may also form as a result of other events, including earthquakes, changes in atmospheric pressure, heavy rains, and variations in water density (Wycoff 1999). Lake Superior’s maritime lake effects and the jet stream can cause severe winter storms with high winds and waves (Eichenlaub 1979; Busch 2008).

The Lake Superior shoreline is varied. Mechenich et al. (2006) characterized the shoreline within the lakeshore using 16 different categories, including exposed rocky cliffs, exposed artificial structures, beaches, gravel beaches, and sheltered vegetated banks.

Shorelines within the lakeshore are dynamic areas capable of rapid change, which is primarily a function of lake level. Mean annual lake levels can fluctuate nearly 2 m (6 ft) from one year to the next, so the conditions are highly variable (National Oceanic and Atmospheric Administration 2014). Beach ridges reflect cyclical changes in lake level that likely has a late Holocene climate signature (Thompson and Baedke 1997; Baedke and Thompson 2000). High-resolution lake-level curves, constructed from coring and radiocarbon dating, show an approximately 160-year cycle as well as an approximately 33-year cycle in lake level. Another cycle, approximately every 1,000 years, may exist in the record as well, but additional sampling is needed for better definition in the 2,500–5,500-year BCE time period. At Sleeping Bear Dunes National Lakeshore, in the lower peninsula of Michigan, corrugated plains and beach ridges record the drops of the Nipissing phase lake levels with intermittent ridges recording five or six discrete stands (periods of relative stability). Evidence of former lake levels at Pictured Rocks National Lakeshore includes paleosols, charcoal layers, and plant remains. The Carter Site, near Grand Marais, contains sand-buried lagoon deposits as a record of a long-standing lake level inland from its present location (Thornberry-Ehrlich 2010). A signature beach ridge is formed approximately every 22 years in response to a lake-level fluctuation of about 0.5 to 0.6 m (1.6 to 2.0 ft) (Thompson and Baedke 1997; Baedke and Thompson 2000; Kevin Kincare, US Geological Survey, geologist, written communication, 4 October 2021). Between 1999 and 2014, the Great Lakes experienced water-level lowering below long-term averages (Tip of the Mitt Watershed Council 2021). Since that time, water level has been increasing. A modern, record high-water cycle in Lake Michigan and Lake Superior is causing dramatic erosion around the basins.

Sea Caves and Other Shoreline Erosional Features

Wind and waves continually sculpt (erode) bedrock shorelines at the lakeshore. Characteristic erosional features of the bedrock shoreline include cliffs (described in the “Pictured Rocks” section), sea caves, arches, windows, sea stacks (spires or pinnacles), embayments, and rocky headlands (fig. 15; Thornberry-Ehrlich 2010). Many of the erosional features are part of a weathering continuum wherein one feature is formed and with further weathering becomes another. For instance, as a rocky headland forms, jutting out into the lake, undercutting may create an arch. With more narrowing, a window may form as rock is removed above the wave base. When the arch/window collapses,

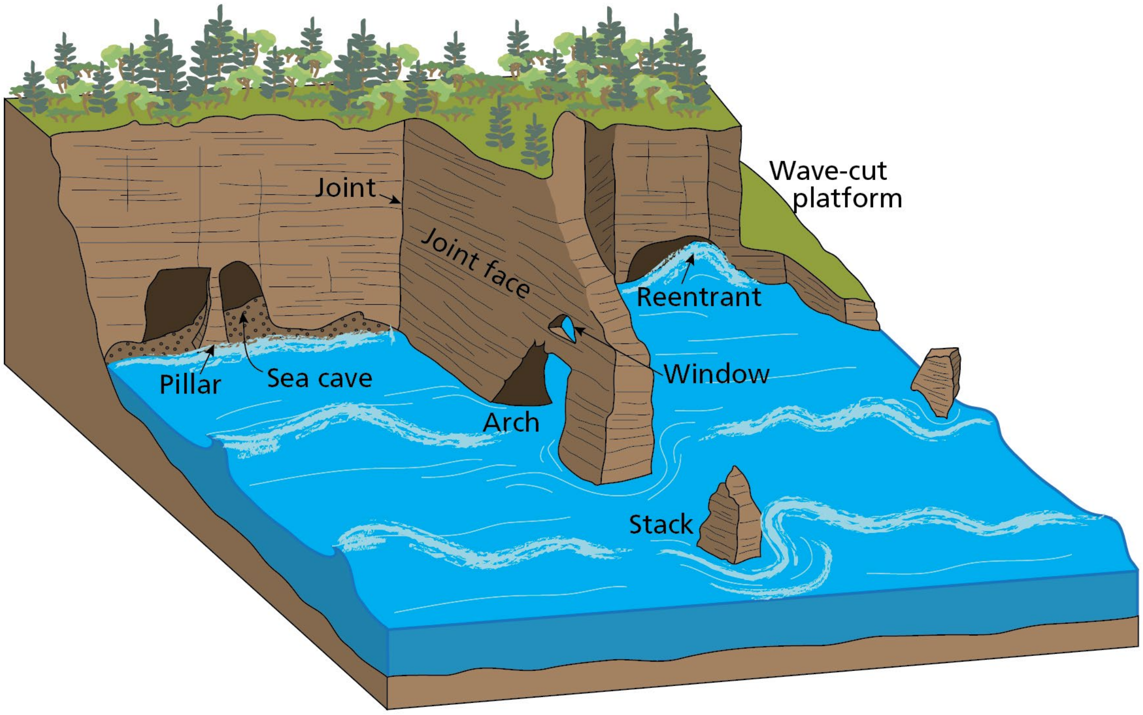


Figure 15. Schematic diagram of erosional features along the Pictured Rocks cliffs. Waves from Lake Superior carve the rocky shorelines of the lakeshore. Sea caves form along the shoreline where waves scour cavities. Pillars may separate sea caves. Where joint faces are oriented perpendicular to the shoreline, a thin fin of rock may extend into the lake. Arches and windows form where waves remove material from the fin. When these features collapse, stacks may remain beyond the shore. Wave-cut platforms and reentrants form where large portions of rock are removed above the shoreline and where small embayments scallop the shoreline, respectively. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Nuhfer and Dalles (2004, figure 9).

sea stacks persist until ultimately being weathered away into the lake. The type of feature created depends on the nature of the bedrock and the orientation of its exposure to the waves of Lake Superior.

Caves are naturally occurring underground voids such as solutional cavities, lava tubes, sea caves, talus caves (a void among collapsed boulders), regolith caves (formed by soil piping), and glacier caves (ice-walled caves) (Toomey 2009). Sea caves are recent features carved into the ancient bedrock at the lakeshore. Sea caves typically form where less erosion-resistant layers, exposed at water level, are overlain by solidly cemented, thickly bedded, more resistant layers. Waves erode the less durable layers, incising shoreward. The more resistant layers remain as overhangs to incised areas called “reentrants.” As the reentrant deepens and sometimes coalesces with other reentrants, a sea cave forms until the overhang eventually collapses (Wright 1997; Nuhfer and Dalles 2004). The sedimentary properties of the Chapel Rock Member of the Munising Formation (geologic map unit **Cm**) with its planar bedding, soluble calcium carbonate cementing material, and layers of resistant sandstone interlayered with weaker beds, lend themselves to the formation of sea caves and arches (fig. 16). Sea caves (and in winter, ice caves) occur along the shoreline where this unit crops out. Perched sea caves (located above the modern shoreline) are evidence that water level was higher about 10,000 years ago (Walt Loope, US Geological Survey, retired research ecologist, conference call, 29 July 2020). Faults and joints may initiate embayment and cave formation because they are zones of weakness where erosion and weathering concentrate. Wind and waves are not the only agent of shoreline change at Lake Superior. If water that seeps along cracks and fractures in the cliff forming rocks freezes it will expand, wedging rock apart in a process called frost weathering.

Wave-cut platforms, also referred to as “benches,” are erosional shoreline features present at the lakeshore. They represent periods of relatively constant lake water levels. Waves and cobbles rolled by the waves erode these platforms. Wave-cut platforms are most common where less resistant shaly sandstone lies over more resistant, cemented sandstone near the lake’s surface. These frequently record older, higher lake levels.

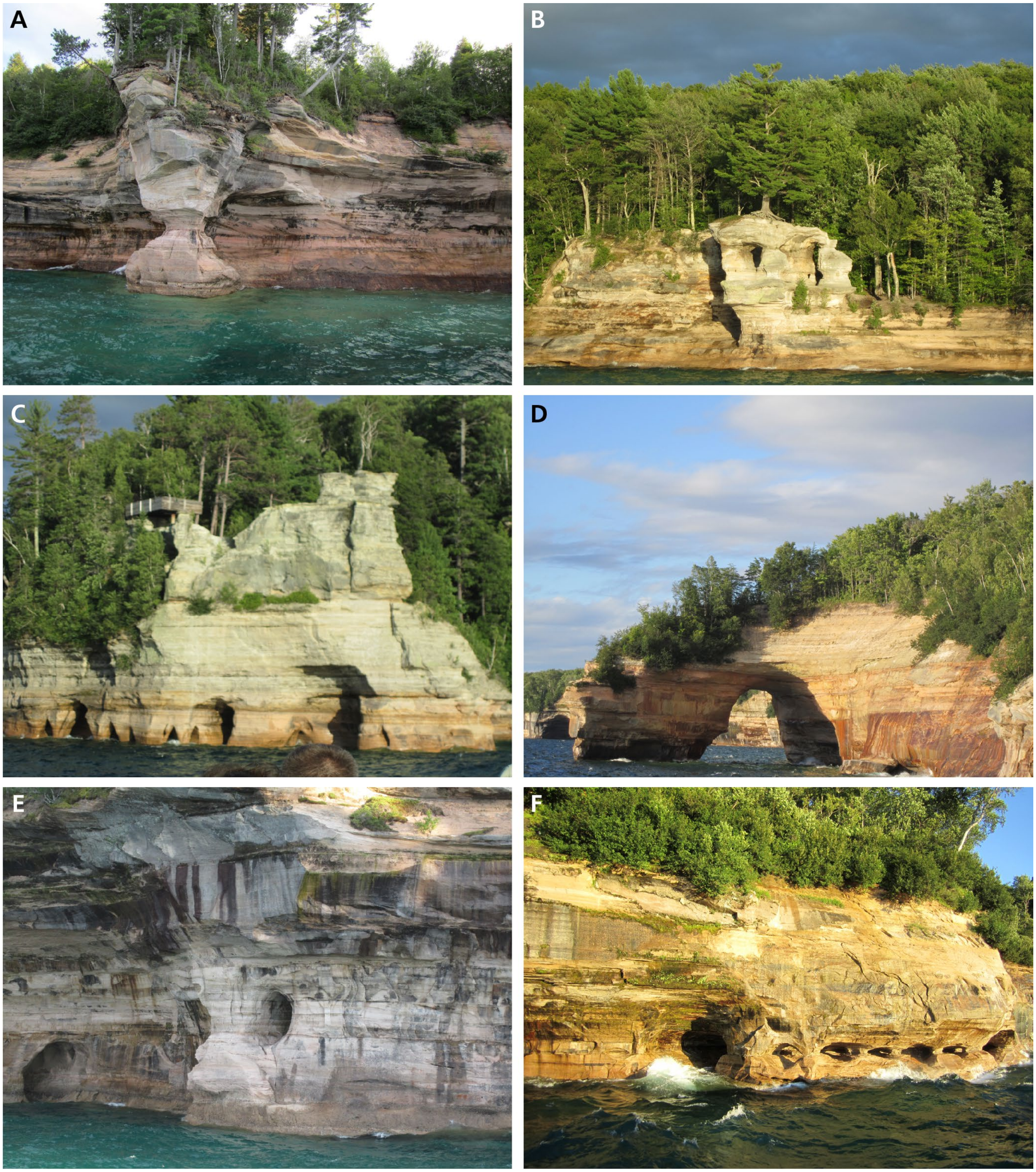


Figure 16. Photographs of wave-sculpted rock outcrops.
(A) A feature called the flower vase formed as waves batter a headland from two directions. (B) Miners Castle formed as arches, spires, and fins coincide in the Munising Formation. (C) Miners Castle overlook is overwhelmed with visitors during high season. Plans involving its renovation over a structurally unstable bedrock is a resource management concern. (D) A broad sea arch formed as waves breached a thin fin of rock at a headland. (E) Sea caves formed at levels where waves repeatedly reach. (F) Sea caves and cavities formed (and continue to form) along weaker layers in the bedrock at certain levels. Photographs by Trista L. Thornberry-Ehrlich (Colorado State University) taken in summer 2009.

In shoreline areas not composed of bedrock (e.g., Grand Sable banks), other shoreline erosion features form. Thick glacial tills underlie most of the land within the lakeshore boundary. Glacial-till bluffs form where waves are eroding into the thick, unconsolidated material deposited by the Pleistocene glaciers. Erosion of these bluffs produces slumping and landslide scars (see "Geologic Hazards" section). This erosion process also provides vast amounts of sediment to the shoreline system of sandscapes. Erosion is most prolific in the springtime when the glacial till is saturated with water and the wave energy is high (Nuhfer and Dalles 2004).

Caves and Associated Landscape Management

Cave features are nonrenewable resources. The Federal Cave Resources Protection Act of 1988 requires the identification of "significant caves" in NPS areas, the regulation or restriction of use as needed to protect cave resources, and inclusion of significant caves in land management planning. The act also imposes penalties for harming a cave or cave resources and exempts park managers from releasing specific location information for significant caves in response to a FOIA request (see "Guidance for Resource Management" chapter).

A park-specific cave management plan has not yet been completed for the lakeshore. The NPS Geologic Resources Division can facilitate the development of a cave management plan. Such plans include a comprehensive evaluation of current and potential visitor use and activities, such as climbing, which is currently restricted at caves in the lakeshore. Moreover, a cave management plan would likely discuss issues associated with ephemeral ice caves, which can form along the lakeshore in a harsh winter. Cave management plans propose ways to survey and study known caves and discover new ones. Cave management plans also discuss caves as bat habitat.

Toomey (2009)—the *Geological Monitoring* chapter about caves and associated landscapes—described methods for inventorying and monitoring the following cave-related vital signs: (1) cave meteorology, such as microclimate and air composition; (2) airborne sedimentation, including dust and lint; (3) direct visitor impacts, such as breakage of cave formations, trail use in caves, graffiti, and artificial cave lighting; (4) permanent or seasonal ice; (5) cave drip and pool water, including drip locations, rate, volume, and water chemistry, pool microbiology, and temperature; (6) cave microbiology; (7) stability issues associated with breakdown, rockfall, and partings (solutional remnant of rock that spans a passage from floor to ceiling); (8) mineral growth of speleothems, such as stalagmites and stalactites; (9) surface expressions and processes that link the surface and the cave environment, including springs, sinkholes, and cracks; (10) regional groundwater levels and quantity; and (11) fluvial processes, including underground streams and rivers. This information would augment cave management planning.

Sandscapes

The shoreline environment is dynamic with shifting sands evolving into ephemeral landforms that can persist for years or change in a single storm. Shoreline (coastal) resources—shaped by waves, tides, wind, sediment supply, and lake level—may include tidal flats, estuaries, dunes, beaches, and barrier islands (Bush and Young 2009). The lakeshore contains sand-based features such as dunes (see "Aeolian Features and Processes" section), beaches, beach ridges, sand banks, and sand spits that combine to form sandscapes (collections of landforms, however temporary, composed of loose particles that are transported and reworked by wind and water). Development of sand landforms requires (1) a source of sand, (2) wave energy to erode sand from its source and transport it elsewhere, and (3) a sheltered place to accumulate (Nuhfer and Dalles 2004). Sandscapes at the lakeshore are mostly composed of postglacial deposits and shoreline sediment (surficial geologic map unit **Qc**), which is weathered from glacial-till deposits.

Beach configuration depends on wave conditions and shoreline morphology. Beaches form where waves have stacked sand onto the shoreline. At the lakeshore, beach deposits commonly accumulate in protected coves, where sand circulates, and at the bottom of exposed glacial bluffs (fig. 17). Storm waves move sand from the beach to offshore bars, leaving behind cobble-covered surfaces. By contrast, gentler waves move sand from the offshore bars onto the beach to form gently sloping beaches. Beach height, or the measure from the mean water level to the highest point on the beach, is a function of wave energy, the direction of dominant wave approach, sediment supply, grain size, and lake level stability (Robert Young, Western Carolina University, geologist, written communication, 26 January 2022). The elongated linear apex that forms parallel to the shoreline is called a beach ridge. Swash is the rush of water up the beach after the breaking of a wave and a function of wave energy. The more vigorous the swash, the farther sand moves inland unless a bluff blocks the way (Engstrom 1974a, 1974b; Robert Young, Western Carolina University, geologist, written communication, 26 January 2022). Sand commonly accumulates in sheltered embayments as local beaches between headlands as well as at the base of the Grand Sable banks. Beaches also occur at stream mouths where incoming fluvial sediments mix with lakeshore sediments (fig. 18). For example, Twelvemile Beach

Figure 17. Photograph of an offshore sand bank.
Sand banks form where sufficient sediment is available and wave conditions allow the local accumulation of sediments. Depending on lake levels, sand banks may be submerged or exposed. Such features may provide bird habitat. Photograph by Trista L. Thornberry-Ehrlich (Colorado State University) taken in summer 2009.

Figure 18. Photograph of the Sable Creek delta into Lake Superior.
Steep river channels funnel water and sediment downslope onto the Lake Superior shoreline where longshore currents and wave action wash the sediment along the coast. Sometimes, these outlets become blocked, forming lagoons. Photograph by Trista L. Thornberry-Ehrlich (Colorado State University) taken in summer 2009.

(composed of surficial geologic map unit **Qb**) is a mixed sand and gravel beach and forms where stream mouth beaches coalesced to form one long strand (Thornberry-Ehrlich 2010; VanderMeer et al. 2020).

At the interface of water and land, sand is very mobile, and landforms change quickly. Sand banks are large deposits of sand forming a mound, hillside, bar, or shoal. Sand banks are commonly submerged but may appear during low-water conditions or between wave swells. Sand spits (elongate "fingers" of sand) can be transitional or connected. Sand spits typically develop on the sides of jutting headlands leeward to the dominant wave direction.

Coastal Issues

Because of the current record high lake levels in Lake Superior, lakeshore resource managers need a better understanding of shoreline processes in order to plan future development at the lakeshore. For example, commercial kayak businesses need new access sites (Bruce Leutscher, Pictured Rocks National Lakeshore, chief of Science and Resource Stewardship, conference call, 29 July 2020).

Resource managers at the lakeshore have some concern that anthropogenic activities in communities such as Grand Marais may negatively impact lakeshore resources and locally change the shoreline dynamics. To protect the marina inlet at Grand Marais, the US Army Corps of Engineers installed a large stone breakwater in 1990. The breakwater disturbed the natural regime by preventing natural longshore drift from moving sediments eastward and may cause a potential pileup and artificial stabilization of sand deposits farther west. If the sediment infilling down shore of the breakwater is voluminous enough and consists of an appropriate grain size to prevent the local undercutting of the lakeshore bluffs (provide sediments upslope to the dunes), the active dune fields (e.g., Grand Sable Dunes) may revegetate, stop migrating with prevailing winds, and stabilize. Progressive aerial photographs that document, and could be used to monitor, shoreline changes as a result of the breakwater at Grand Marais are invaluable data. Currently, photographs exist for every three to five years in the past few decades (Thornberry-Ehrlich 2010). Some multimedia data sets are available on the NPS Integrated Resource Management Applications (IRMA): https://irma.nps.gov/Datastore/Search/Quick (search terms: multimedia, and unit: Pictured Rocks National Lakeshore). The Michigan Geological Survey has used drone surveys to provide real-time assessments of geomorphic changes and shoreline features in motion. For Lake Michigan, this work provided data that have become the basis for bluff-failure analyses (John Yellich, Michigan Geological Survey, chief geologist, conference call, 29 July 2020). This technology and methodology are applicable to monitoring Grand Sable Dunes and other shorelines at the lakeshore.

Within the lakeshore, a stretch of shoreline at Sand Point has a stone revetment that is disrupting natural coastal processes. The revetment was originally installed in the 1990s to protect homes at risk of damage from lake level rise during the 1980s. The revetment area at lakeshore headquarters (the old Coast Guard station) is prone to flooding since it was constructed during historic, low lake levels. In 2009, the revetment was considered for removal as part of the Great Lakes Restoration Initiative (Thornberry-Ehrlich 2010). That initiated a long (more than seven years) and complex process to gain a thorough understanding of the local shoreline processes and impacts of removing the revetment. During this time, however, lake levels rose, and the revetment was ultimately buried in sediment. Resource managers currently plan to leave the revetment buried with the understanding that this is only a temporary solution; so far, deposition is occurring, and Sand Point is "growing" even at high lake levels (Bruce Leutscher, Pictured Rocks National Lakeshore, chief of Science and Resource Stewardship, conference call, 29 July 2020). When lake levels cyclically drop again, the revetment will possibly be re-exposed and the sand will wash away, but not the large rocks of the structure (Walt Loope, US Geological Survey, retired research ecologist, conference call, 29 July 2020). The current resource management strategy is recurring maintenance by removing rocks as they become exposed (Bruce Leutscher, Pictured Rocks National Lakeshore, chief of Science and Resource Stewardship, conference call, 29 July 2020).

Shoreline stabilization areas also include the Au Sable light station, which is armored by gabions and timbers, and Sand Point, where a rock revetment was originally installed as a flood control measure but is now mostly buried in sand (Thornberry-Ehrlich 2010; National Park Service 2020c). When stabilization is not feasible, facilities may be relocated, such as Road H-58, which was realigned near Sullivan's landing on Twelvemile Beach because of shoreline erosion (National Park Service 2016).

Included in the lakeshore boundary is 0.4 km (0.25 mi) of lake surface beyond the dynamic shoreline. Submerged cultural resources occur within this area and are of interest to resource managers. The jurisdiction over the submerged portion of the lakeshore is unclear (Thornberry-Ehrlich 2010).

Shoreline Response to Lake-Level Change

Lake levels have changed profoundly in the recent past and will continue to change (Nuhfer and Dalles 2004). Throughout the 1900s, the Great Lakes showed a trend toward increasing lake levels (Engstrom 1985), but since 1998, the levels were dropping to near 1930s Dust Bowl conditions. In 2007, the lake was 56 cm (22 in) below normal (Climate Change Response Program 2012). An extreme winter in 2013–2014 caused a lake-level spike, and in turn, accelerated shoreline erosion and change. When lake levels are high, beaches throughout the lakeshore are greatly reduced by considerable erosion with the exception of areas where sediment supply is counteracting the high lake level such as Sand Point (Thornberry-Ehrlich 2010; Robert Young, Western Carolina University, geologist, written communication, 26 January 2022). In 2020, the lake was again approaching record high levels (GRI conference call participants, conference call, 29 July 2020). Lake levels lowered again in 2021 (Laura Waller, Pictured Rocks National Lakeshore, chief of Science and Resource Stewardship, written communication, 9 September 2021).

Lake levels and shoreline changes are controlled by myriad factors such as isostatic rebound, sedimentation patterns, anthropogenic influences, and climate (Engstrom 1985; Nuhfer and Dalles 2004). As a result of uneven isostatic rebound, the Lake Superior basin is tilting, causing the northern and eastern portions of the lake's bottom to rise relative to the southern portion (Engstrom 1985). Potentially this tilt will cause southern shorelines to recede and lake level to rise; however, other factors, such as climate change, will have impacts (see "Climate Change" section).

In contrast to global oceans, the water level in the Great Lakes is not directly connected to the melting of polar ice. Thus, contrary to marine coastal settings where relative sea level is predicted to rise, climatic models tentatively predict lake levels will drop. Lower lake levels will impact groundwater recharge, cause nearby streams and wetlands to shrink or disappear, and necessitate harbor and channel dredging to maintain shipping facilities. Dredging could expose contaminated sediments (Pendleton et al. 2007). Lower lake levels could also expose submerged archeological resources such as shipwrecks or prehistoric sites (National Park Service 2011). Impacts to visitor use from lower lake levels and climate change include a shorter winter recreation season, infrastructure problems such as high-and-dry docks, and new navigational hazards such as sand bars (National Park Service 2011).

GRI scoping participants noted a need to study lake-level history. Possible investigations include using light dating (optically stimulated luminescence) to determine the time of sand burial. Such studies already exist for sands at Sable Creek (Thornberry-Ehrlich 2010). A broader scope project would make an excellent graduate-level or Scientists in Parks (SIP) study (see "Guidance for Resource Management" chapter).

Monitoring and Research of Lake-Level and Shoreline Change

GRI conference call participants (29 July 2020) listed the need for a better understanding of large-scale sediment movement along the shoreline and how that impacts features such as the dunes, Grand Marais, and Sand Point. Resource management specialists at the National Park Service are examining and considering the National Oceanographic and Atmospheric Administration (NOAA) Lake Level Viewer (http://coast.noaa.gov/llv/) as a monitoring tool for lake level changes in Great Lakes national parks and lakeshores (Lynda Bell, NPS Water Resources Division, sea level specialist, written communication, 21 January 2015). The US Geological Survey/National Park Service Water Quality Partnership Program at Sleeping Bear Dunes National Lakeshore has recently completed an investigation on the role of beaches and shallow waters in identifying areas prone to botulism toxin production and how it is related to changes in lake levels and surface water temperatures (Lafrançois et al. 2011). This work in the Great Lakes region is being applied and used to enhance the understanding of lake-level and shore-level change in all of the Great Lakes parks, including Pictured Rocks National Lakeshore (Lynda Bell, NPS Water Resources Division, sea level specialist, written communication, 21 January 2015).

National Park Service (2016) noted a need to use shoreline features and First Peoples' history to identify and interpret human history along the shoreline. Some of these features might be submerged (see "Geologic Significance and Connections").

Shorelines are dynamic, any inventory of these features provides merely a snapshot in time. Thus, an inventory followed by long-term monitoring is needed to establish trends, understand change through time, and predict future conditions. In the *Geological Monitoring* chapter about coastal features and processes, Bush and Young (2009) described the following methods and vital signs for monitoring coastal features and processes: (1) shoreline change, (2) coastal dune geomorphology, (3) coastal vegetation cover, (4) topography/elevation, (5) composition of beach material, (6) wetland position/acreage, and (7) coastal wetland accretion. In the *Geological Monitoring* chapter about marine features and processes, Bush (2009) described five methods and vital signs for monitoring marine features and processes, which also may be applicable to lakeshore settings: (1) general setting of the environment, of which water depth is the primary indicator; (2) energy of the environment, waves, and currents; (3) barriers, including reefs and other offshore barriers, which block energy; (4) seafloor composition or substrate; and (5) water column turbidity.

Surficial Deposits

The evolution of the landscape at the lakeshore is intimately tied to the glacial and post-glacial isostatic rebound history of the region. When the heavy ice sheets melted, the land rebounded upward but also unevenly. All things being equal, isostatic rebound causes the land to rise which forces shorelines to retreat and relative lake level to drop. In the case of differential isostatic rebound, the rebound rate of the lake's outlet versus the rebound rate of a particular area dictates lake-level response. Where a large distance between the outlet (the Saint Marys River) and other parts of the lake exists, some places rebound at significantly different rates than the outlet. For example, Duluth is rebounding at a lower rate than the outlet so is sinking relative to the outlet, even though Duluth and the Saint Marys River are both actually rising. The northeast shore of Lake Superior (Ontario) is rebounding at a higher rate than the outlet, and the shoreline is locally retreating (Larsen 1987; Kevin Kincare, US Geological Survey, geologist, written communication, 5 October 2021). At the lakeshore, differential isostatic rebound has caused lake transgressions (lake level rises) that inundate areas. At these higher shorelines, stabilizing vegetation dies back, and glacial outwash and lake sediments are exposed to wave and wind action. These sediments can be reworked by wind or water to become part of a beach or dune. Prevailing wind whips these sediments up the shoreface to upland areas where they contribute to dune formation and reactivation (Thornberry-Ehrlich 2010).

Surficial deposits, which record the glacial and post-glacial part of the lakeshore's geologic history, are unconsolidated and formed during the past 2.6 million years (the Quaternary Period composed of the Pleistocene and Holocene Epochs; see table 1). Surficial deposits are commonly differentiated or described by geologic process or depositional environment, rather than rock type. Glacial and post-glacial deposits (surficial geologic map units **Qts**, **Qd**, **Qkt1–6**, **Qs**, **Qsg**, **Qg**, **Qm**, **Qpm**, **Qe**, and **Qdr**) make up the majority of the sediment that has been recently reworked and redeposited by Earth surface processes. Additionally, as Earth's climate warmed and the glaciers retreated at the end of the Pleistocene Epoch, a series of glacial lakes formed at the melting edge of the glacial ice sheet, which left stranded shorelines at higher levels than modern Lake Superior (see "Glacial Features" section).

Recent surficial deposits—including shoreline sediments, organic sediment, aeolian (windblown) grains, and fluvial (stream) sediment (surficial geologic map units **Qb** and **Qp**; see table 3)—are constantly being deposited and reworked by Earth surface processes on the landscape. As described in the "Sandscapes" section, beach sand (**Qb**) fringes much of the dynamic shoreline at the lakeshore. Twelvemile Beach, for example, is composed of this unit. Organic sediments (**Qp**), including peat, are collecting in swamps, kettles, and marshes at the lakeshore. These are useful for dating purposes because they contain organic carbon and fossil pollen (see "Paleontological Resources Inventory, Monitoring, and Protection" section). As described in the "Fluvial Features" section, stream sediments are collecting along local streams and rivers within the lakeshore.

Grand Sable Banks

The Grand Sable banks and Grand Sable Dunes are located at the northeastern end of the lakeshore (fig. 19). The banks are remnants of a glacial kame terrace that formed along the retreating edge of a glacier. The banks form a platform. Active sand dunes cap the banks as perched dunes (see "Aeolian Features and Processes" section), which are among the highest elevations within the lakeshore at 280–300 m (920–980 ft) above mean sea level. Dramatic relief is represented by the underlying bluff facing the lakeshore (VanderMeer et al. 2020). Springs emerge from the base of the banks to flow into Lake Superior (fig. 19; Thornberry-Ehrlich 2010).

The northern bluff of the highest glacial meltwater kame terrace (**Qkt1**; see "Glacial Features" section) makes up the majority of the banks (VanderMeer et al. 2020). Compositionally, the banks consist of a basal layer of fine-grained sediments, overlain by interbedded sand and silt, then by alluvial sand and gravel (fig. 19). The banks were reworked by wind with buried soils, in situ trees, and other organic remains (Anderton and Loope 1995; Hunt et al. 2008).

The Grand Sable banks and Grand Sable Dunes preserve a record of past lake levels (Thornberry-Ehrlich 2010). When lake levels rise, the bluffs and dunes along the lakeshore become more active or reactivated; sand is washed or blown upslope to join the dunes (VanderMeer et al. 2020). When lake levels drop, vegetation may become established and thereby begin to stabilize the landscape, anchoring the loose sediments in place. This cycle has occurred at least a dozen times in the last 5,000 years (Thornberry-Ehrlich 2010).

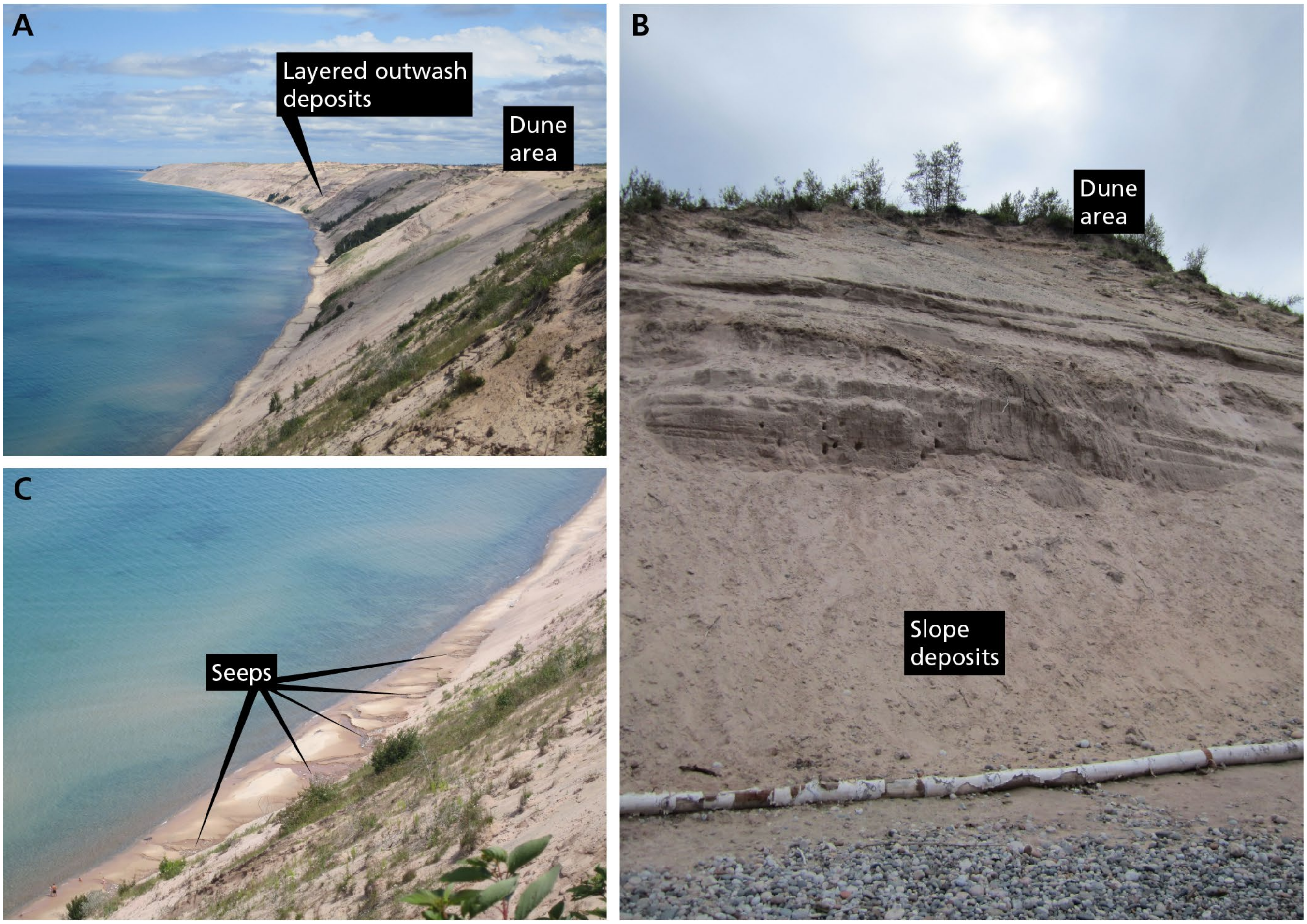


Figure 19. Photographs of the Grand Sable banks.
(A) Active dune fields are perched atop layered, glacial outwash deposits at the Grand Sable banks; view is looking eastward toward Grand Marais. (B) From below, the layered nature of the sediments forming the core of the banks is apparent. Deposits formed by slope movements mantle the base of the slope. (C) Seeps emerge from the base of the banks, and discharged water courses into Lake Superior. Photographs by Trista L. Thornberry-Ehrlich (Colorado State University) taken in summer 2009.

Around 5,000 years before present, the Grand Sable banks destabilized because rising lake levels created a steep exposure of kame terrace (glaciofluvial) sediments (Marsh and Marsh 1987; Hunt et al. 2008).

Grand Sable Lake formed when the level of the Great Lakes was high enough to overrun the shoreline banks (bluffs). Wave and wind action eroded sand, which was deposited down current or eastward toward Lonesome Point, east of Grand Marais. This flowing sand also dammed Sable Creek, impounding Grand Sable Lake. At the core of the Grand Sable banks is a paleovalley (ancient valley now filled with sediments) and paleosols (ancient, buried soil horizons). These ancient features are evidence of burial events triggered by rising lake levels. Based on radiocarbon dating, these burial events are cyclic, occurring as early as 5,000, 3,455, 1,455, and 655 cal yr BP and most recently about 1900 (Larsen 1985; Marsh and Marsh 1987; Anderton and Loope 1995; Regis and Anderton 1999).

A portion of the Grand Sable banks and Grand Sable Dunes was designated a research natural area (RNA; a natural laboratory or classroom and part of a national network of field ecological areas in ecosystems with very limited public use or disturbance) by the National Park Service. This designation is for research and education, and to maintain biological diversity. The Grand Sable banks and Grand Sable Dunes RNA offers a pristine environment for scientific study of climate change, lake level history, coastal landforms, soil development, rare plant communities, and vegetation succession (National Park Service 2019). This designation suggests that research should have management priority in contrast with an emphasis on visitor access (Walt Loope, US Geological Survey, retired research ecologist, conference call, 29 July 2020).

Aeolian Features and Processes

Aeolian processes refer to windblown erosion, transportation, and deposition of sediments (Lancaster 2009). Features created by aeolian processes include dunes, loess, sand sheets, desert pavement, yardangs, and alcoves. As of January 2020, at least 48 designated units of the National Park System contain sand dunes. The NPS Geologic Resources Division Aeolian Landforms website, https://www.nps.gov/subjects/geology/aeolian-landforms.htm, provides additional information.

Aeolian features at the lakeshore include dunes, interdune swales, perched dunes, and barrier sand spits (which are also a shoreline feature; geologic map unit **Qb**) (Thornberry-Ehrlich 2010; VanderMeer et al. 2020). Glacial till banks and bluffs along shorelines formed upland areas and are the source of sediment for aeolian features. Wind erodes the banks and bluffs by drying them and scouring their surface. Western prevailing winds initially accumulated lake deposits (now stranded) and sand dunes at Lonesome Point (downdrift from glacial upland areas) during the Nipissing phase about 5,000 cal yr BP (Larsen and Schaetzel 2001; VandeMeer et al. 2020). Grand Sable Dunes also began forming at this time. High water undermined nearby bluffs freeing vast amounts of sediment; wind blew the sediment (sand) into a series of overlapping sand dunes (figs. 20 and 21; Thornberry-Ehrlich 2010). The largest dune formed 600 years ago at Grand Sable (Thornberry-Ehrlich 2010). Today, bluff collapse threatens dune fields; if the bluff face is disturbed or starved of sediment, the bluff could collapse, bringing the perched dune down with it (Bruce Leutscher, Pictured Rocks National Lakeshore, chief of Science and Resources Stewardship, conference call, 29 July 2020; Kevin Kincare, US Geological Survey, geologist, written communication, 5 October 2021).

The dunes at the Grand Sable banks, which initially accumulated during the Nipissing phase, have been stabilized and destabilized cyclically with fluctuating lake levels. A dune is stabilized naturally by encroaching vegetation. Plant roots hold the sand in place and the dune stops migrating with prevailing winds. When vegetation is diminished or buried by an influx of sand, the dune migrates again and is destabilized. As discussed in the "Lake Superior Shoreline" section, lake level varies in response to climate (precipitation, winter ice cover, temperature) and the degree of isostatic rebound causing the floor of the basin to rise (Thornberry-Ehrlich 2010). Rising lake levels cause waves to undercut the bluffs, which then slump onto the shoreline releasing sediments to wave action. Prevailing winds blow the sediments up to form dunes. Falling lake levels allow the base of the bluffs to restabilize and forestation of the overlying dunes. Thereby lake levels control sediment supply to the dunes. In this way, the dunes contain a record of lake level rise and fall over the past several thousand years that may also be a proxy for climate change.

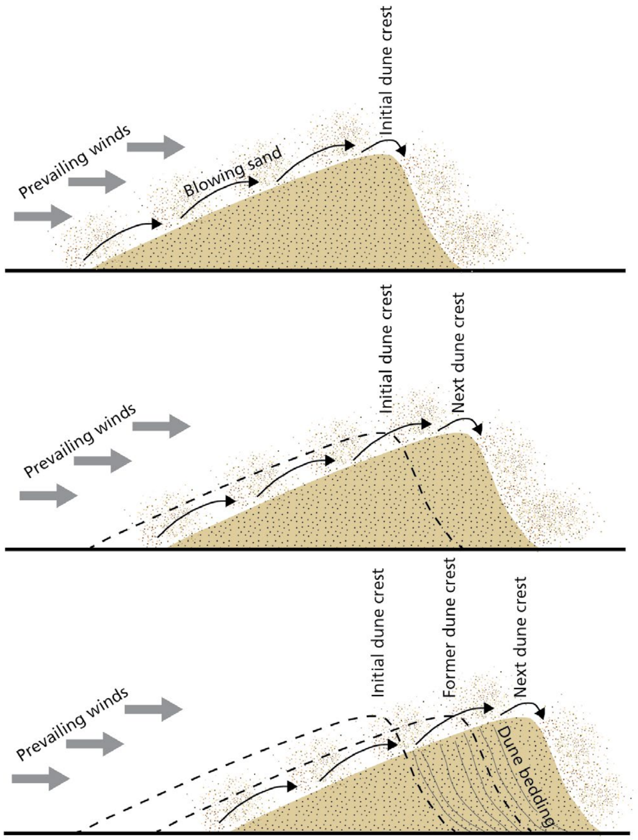


Figure 20. Aeolian sand transportation and dune movement.
Prevailing winds transport sand grains up the dunes, depositing them in cascades down the steep side. At Pictured Rocks National Lakeshore, wind is whipping sand grains up from the Lake Superior shoreline to add to the sand supply for Grand Sable Dunes. This sand then becomes part of the dune, which migrates in the direction of the prevailing winds. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

Massive volumes of shifting sand blown by prevailing winds along the shoreline created inland lakes by damming drainages toward Lake Superior (Thornberry-Ehrlich 2010). These systems are analogous to barrier and back barrier settings in open marine areas. Active, perched dunes cap the Grand Sable banks more than 60 m (200 ft) above today's lake level (fig. 22). Sand blows

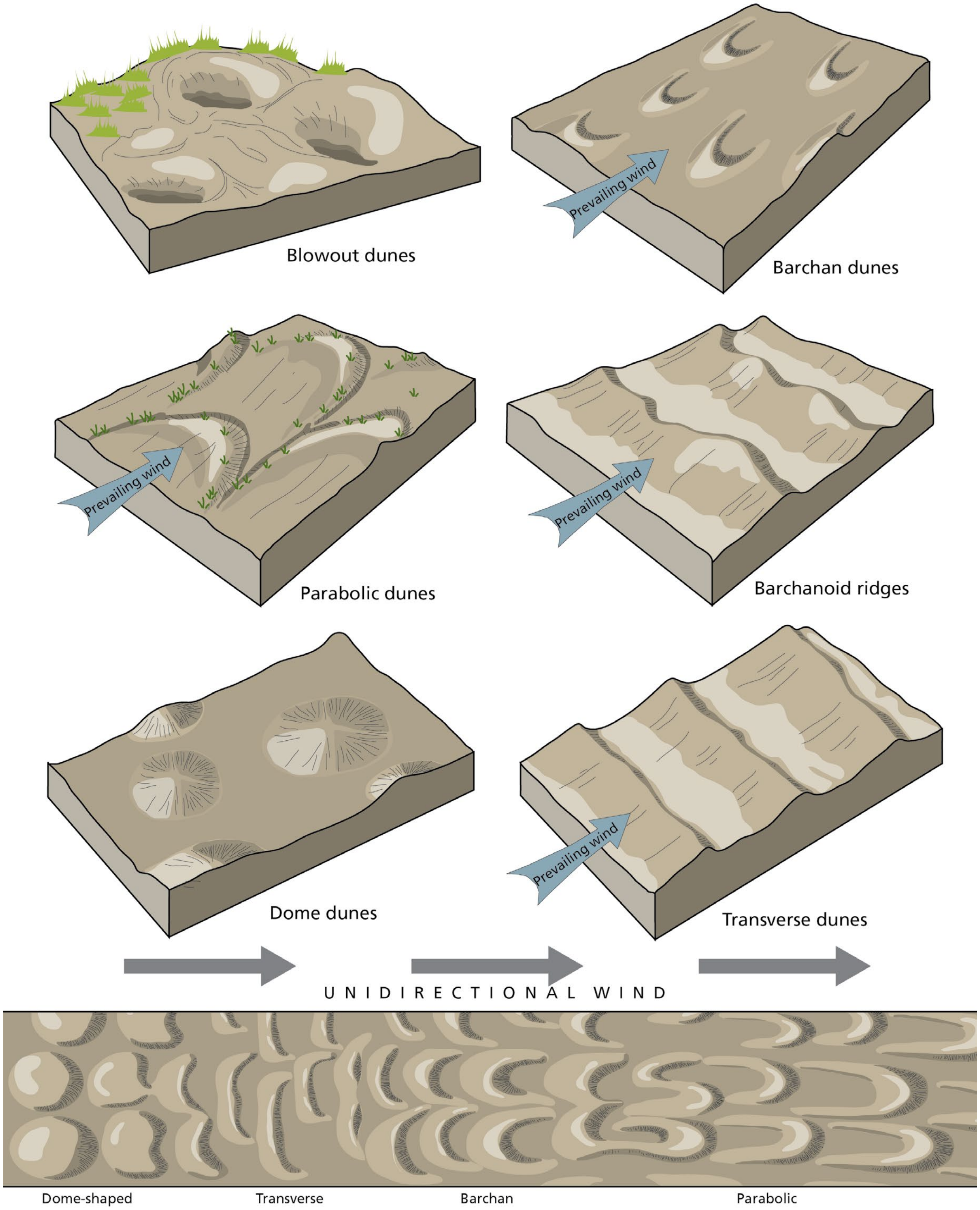


Figure 21. Schematic diagram of dune types and formation.
The primary types of dunes at the lakeshore are perched dunes in blowout and parabolic shapes. Blowout dunes are comparable to parabolic dunes but without the parabolic extensions. Sand supply, wind direction, and interactions among lake levels, groundwater availability, topographic elevation, and vegetation growth affect dune morphology. When the wind is only one direction, round, dome-shaped dunes slowly develop “arms” and form transverse dunes, which then develop into crescent shaped barchan dunes and finally stretched out parabolic dunes. The lowest graphic illustrates barchanoid dune morphologies. Graphics by Trista L. Thornberry-Ehrlich (Colorado State University) after McKee (1983, figure 1) and Fryberger et al. (1990, figure *).

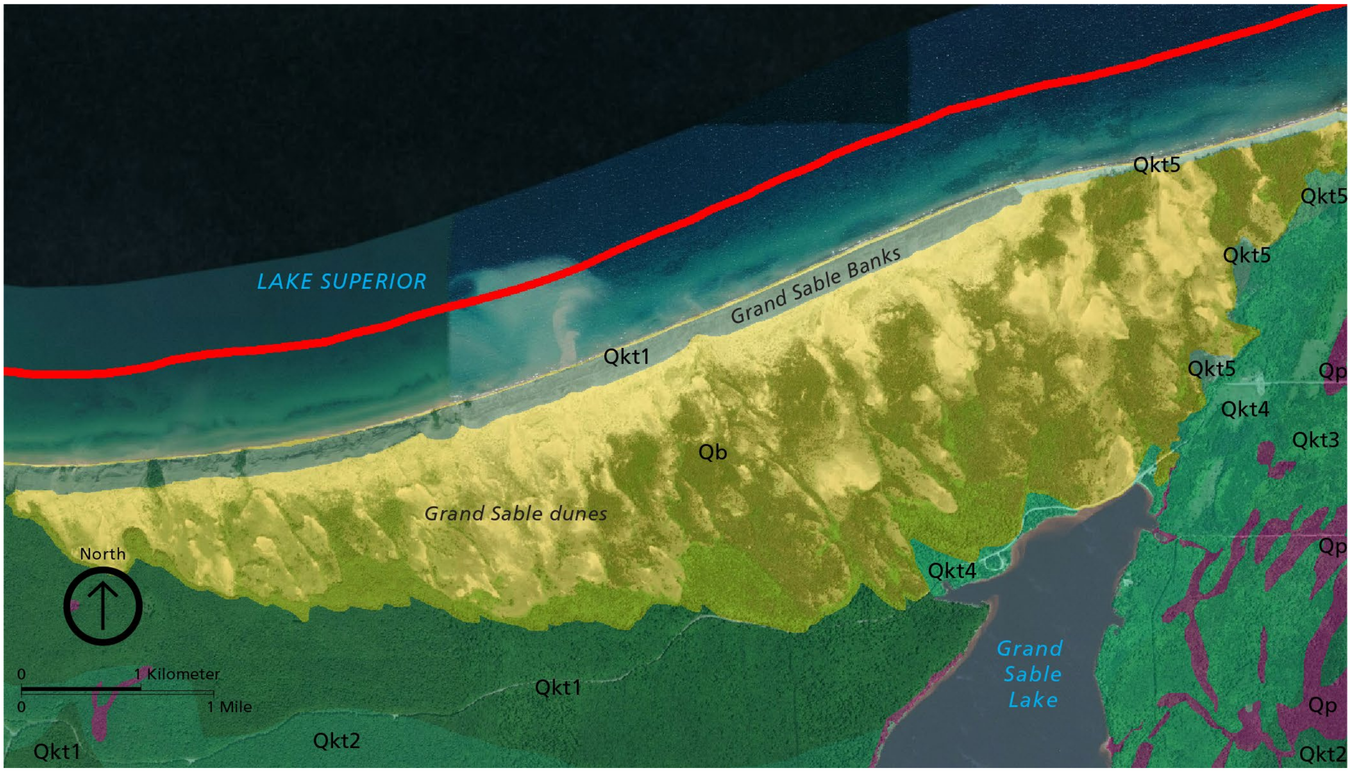


Figure 22. Aerial photograph and geology of the Grand Sable banks.
Surficial geologic map units indicate the aeolian features at the Grand Sable banks. The active dune field is composed of beach sand (Qb). It overlies a platform of kame terraces (Qtk1, Qtk4, and Qtk5), which make up the core of the banks. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with data from VanderMeer et al. (2020) over ESRI World Imagery base map.

up from the lakeshore, loses contact with the wind, and is deposited at the top of the banks. Large stones (larger than sand-size sediments) in the underlying glacial kame terrace sediments (e.g., **Qkt1**) are left behind in what are called "lag" layers, which armor the slope as the wind continually winnows away the sand. Gravel lag deposits are within glacial sediments at the very base of the dunes as well as the very top of the glacial sediments in the interdune or swale areas of the dune fields (Thornberry-Ehrlich 2010).

High winds also contribute to blowdowns (areas of downed trees) that occur in broad swaths through the forests south of the lakeshore. Blowdowns cause more widespread disturbance than fires to lakeshore forests felling the largest trees (Thornberry-Ehrlich 2015). While blowdown areas may seem devastated, it is part of the natural forest cycle along the lakeshore. Where trees are uprooted by strong winds, mounds of soil and sediment are exposed, creating depressions and mounds. This churns the local soils and is an important factor in local soil development (Cary et al. 1979).

Wind Speed

Blowing wind is one of the agents of landform change at the lakeshore. Since 1985, local wind speeds have been increasing at rates approaching 5% per decade. This is likely related to a warming climate. Increasing temperatures of air and surface water, decreases in winter ice, and a reduction in the temperature gradient between air and water have been destabilizing the atmospheric surface layer above the water surface causing an increase in wind speeds (Desai et al. 2009). Increased wind speeds may accelerate erosion of glacial till banks and bluffs, activate or accelerate dune migration, increase tree blowdowns, and promote the formation of aeolian features.

Monitoring aeolian features and processes may aid in predicting the impacts of changing wind speeds on the landforms at the lakeshore. In the *Geological Monitoring* chapter about aeolian features and processes, Lancaster (2009) described the following methods and vital signs for monitoring aeolian resources: (1) frequency and magnitude of dust storms, (2) rate of dust deposition, (3) rate of sand transport, (4) wind erosion rate, (5) changes in total area occupied by sand dunes, (6) areas of stabilized and active dunes, (7) dune morphology and morphometry, (8) dune field sediment state (supply, availability, and mobility), (9) rates of dune migration, and (10) erosion and deposition patterns on dunes.

Fluvial Features and Processes

Fluvial features are landforms formed by flowing water as well as the streams that formed them. About 130.8 km (81.3 mi) of perennial streams and 19.6 km (12.2 mi) of ephemeral streams are within the lakeshore boundary (National Park Service 2016). Nineteen of the streams are named. Miners River is the longest stream in the lakeshore (Mechenich et al. 2006).

Fluvial processes (flowing water) both construct (deposit alluvium) and erode landforms (e.g., river valleys). Fluvial landforms at the lakeshore include stream deltas into Lake Superior, waterfalls, and terraces (remnants of earlier stream levels that existed at a time when a stream was flowing at a higher elevation before its channel cut downward to create a new channel at a lower elevation) (Mechenich et al. 2006). In addition, many perched drainages, separated from the natural water base level by some elevation, occur on the eastern edge of the park (Walt Loope, US Geological Survey, retired research ecologist, conference call, 29 July 2020).

The Lake Superior watershed is very narrow along Pictured Rocks National Lakeshore, only 5–13 km (3–8 mi) wide. On the other side of the watershed divide (denoted by a dashed blue line on fig. 1), water flows south to Lakes Michigan and Huron. As a result of this narrow watershed, streams within the lakeshore are relatively small, with short runs; the channel are steeply incised, however, in response to the land uplifting via isostatic rebound. For example, the land surface at the Taquamenon River outlet (the northernmost portion of its channel) rises relative to its headwaters because of isostatic rebound and has caused the river to cut deeply into the underlying sediments to keep pace (Thornberry-Ehrlich 2010). The lakeshore's few larger streams, such as Miners River, Mosquito River, and Hurricane River, follow channels originally carved by glacial meltwater cascading away from the retreating glaciers (Thornberry-Ehrlich 2010).

Streams, even small streams, act as sediment conveyer belts, reworking and transporting sediment from their headwaters toward their outlets. Most of the streambeds in the lakeshore are composed of mixes of cobble, gravel, sand, and bedrock. Streams underlain by bedrock react quickly to rain and are prone to flash flooding because little absorption by the underlying rock is possible (Mechenich et al. 2006). Pools form in the channels because of the hydraulic action of flowing water over submerged structures such as boulders or logs. Some scouring occurs on the outside of meander bends where flow is highest; in reduced flow areas mud and silt accumulate (Mechenich et al. 2006).

Streams are the source of most of the sediment along the Lake Superior shoreline. On small streams, such as those characteristic of the lakeshore, shoreline processes (longshore currents and wave action) associated with Lake Superior overpower fluvial processes of delta formation (fig. 23; see "Lake Superior Shoreline" section; Thornberry-Ehrlich 2010).

Terraces exist at Grand Marais; however, most elevated terraces date to prior conditions; for example, some formed during the Nipissing phase (see "Geologic Setting and History" section). Others formed during the winter when ice dammed the streams prior to their confluence with the lake, thereby seasonally and locally raising the flow level.

Fluvial and Other Surface Water Issues

The nature of perched drainages and water tables is of concern to resource managers at the lakeshore because of planning needs for septic systems at visitor use areas (Bruce Leutscher, Pictured Rocks National Lakeshore, chief of Science and Resource Stewardship, conference call, 29 July 2020). Detailed water quality discussions are beyond the scope of this report, but the NPS Water Resources Division can provide more information and assistance (see https://www.nps.gov/orgs/1439/index.htm). In the *Geological Monitoring* chapter about fluvial geomorphology, Lord et al. (2009) described methods for inventorying and monitoring geomorphology-related vital signs: (1) watershed landscape (vegetation, land use, surficial geology, slopes, and hydrology), (2) hydrology (frequency, magnitude, and duration of stream flow rates), (3) sediment transport (rates, modes, sources, and types of sediment), (4) channel cross section, (5) channel planform, and (6) channel longitudinal profile.

Inland Lacustrine and Wetland Features and Processes

Lake Superior is the primary lacustrine feature of the lakeshore; however, the lakeshore also has at least 107 smaller inland lakes and lagoons, including Grand Sable, Sevenmile, Lower Shoe, Trappers, Beaver, Little Beaver, Legion, Kingston, Chapel, and Miners Lakes, as well as the informally named Section 36 lake; some of these are within the IBZ (Mechenich et al. 2006; National Park Service 2016).

These features formed by three primary mechanisms: (1) lacustrine areas trapped by accreted sands that were transported by wave action and longshore

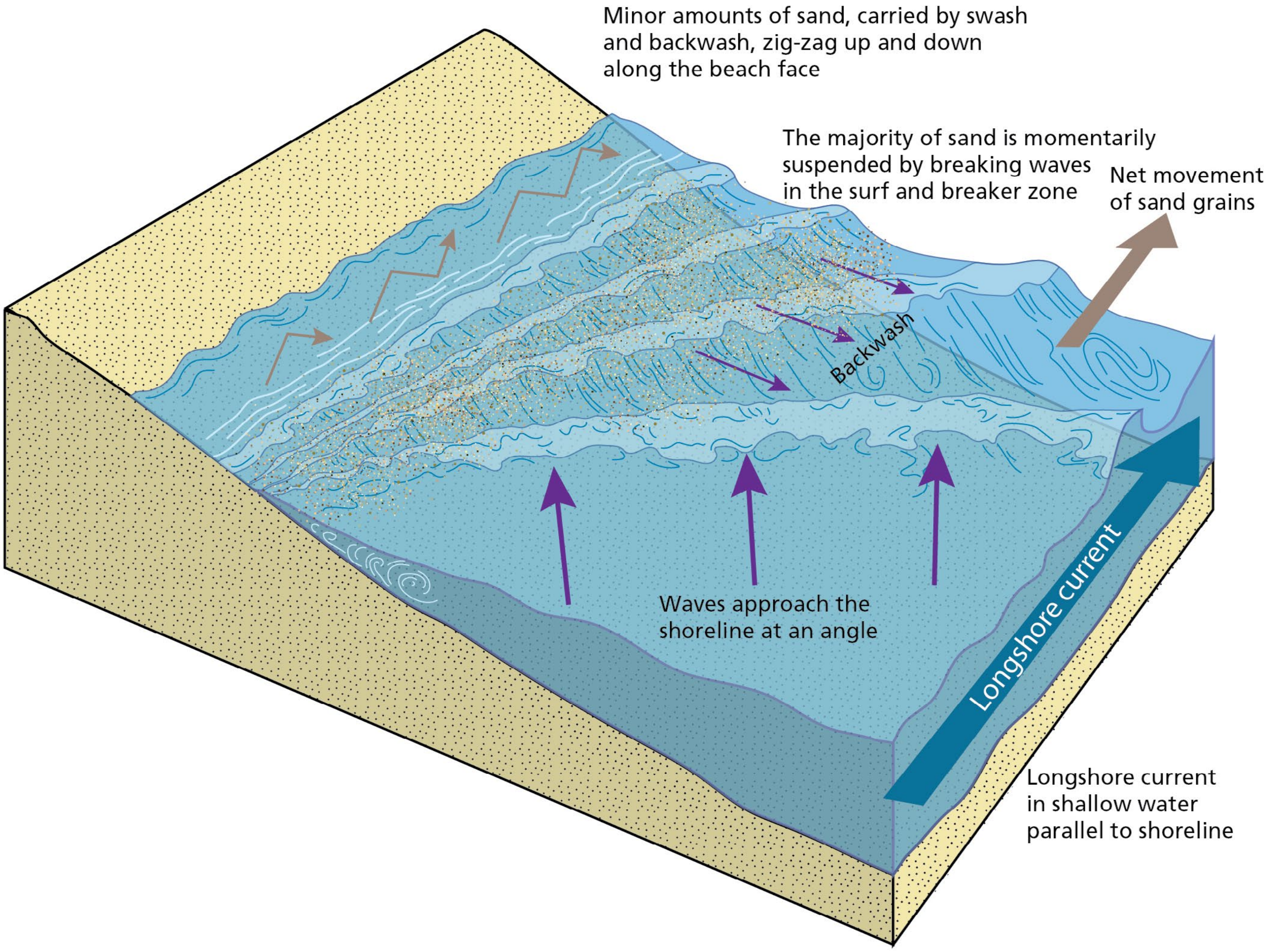


Figure 23. Diagram of longshore drift.
Waves refract as they move onshore, and most of the longshore transport of sand occurs as the sand is suspended temporarily by breaking waves in the surf and breaker zone. Sand grains are transported by waves and longshore currents and deposited in sheltered areas and leeward sides of landmasses. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) based on graphics from Capital Regional District (https://www.crd.bc.ca/education/in-your-community/geology-processes/coastal-sediment) and Rob's [Rob Croslinig] geoblog (http://robcroslinggeoblog.blogspot.com/2011_10_01_archive.html) and information from Peter Rosen and Duncan FitzGerald (Northeastern University and Boston University, respectively, coastal geologists, written communications, 24 and 25 May 2016).

currents along the shoreline (e.g., Beaver Lake); (2) backwater sloughs in large glacial outwash rivers left stranded as recessional features; and (3) kettle lakes, ponds, and wetlands left as stranded glacial ice blocks melted (see "Glacial Features" section). However, a variety of other geomorphic mechanism played a role in lake formation. For example, Grand Sable Lake is a dune-dammed stream. Beaver and Little Beaver Lakes were embayments during the Nipissing phase of Lake Superior. Now, beach ridges separate them from the larger lake. Legion Lake is a closed-basin kettle lake. Miners Lake is a wide, slow-flowing area within the Miners River course. Interestingly, submerged channels in Lake Superior, which align with the modern Miners River course, indicate the river once flowed in the opposite direction as a glacial meltwater channel (Lora Loope, Pictured Rocks National Lakeshore, retired aquatic ecologist, written communication, 30 July 2020). Finally, in contrast to most inland lakes in the lakeshore, which are shallow (about 3 to 6 m [10 to 20 ft] deep), 43-m- (141-ft-) deep Chapel Lake was likely a glacial plunge pool or a deep pool at the foot of a waterfall in a glacial meltwater channel (National Park Service 2020b).

Wetlands and marshes, mapped as peat and muck (surficial geologic map unit **Qp**), are present in upland areas and the shoreline zone. 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 lakeshore are covered in shallow surface water, have water within the root zone most of the year, or may be wet only seasonally. Qualitatively about 25% of the total area within the lakeshore may be wetlands (Mechenich et al. 2006; Department of Environment, Great Lakes, and Energy 2021). 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. Approximately 1,630 ha (4,030 ac) of wetlands are mapped in the NPS Hydrographic and Impairment Statistics database at the lakeshore. At least 49 vernal pools (isolated, temporary wetlands) occur within the IBZ (National Park Service 2016).

Lacustrine and Wetland Management

Apart from the dynamic Lake Superior shoreline, resource managers at the lakeshore also face challenges managing the inland lacustrine features, wetlands, and associated fluvial features within the lakeshore and IBZ. The following references and data sets may provide guidance:

- Assessment of coastal water resources and watershed conditions: https://irma.nps.gov/DataStore/Reference/Profile/648271
- Wetland delineation report for Sand Point: https://irma.nps.gov/DataStore/Reference/Profile/2258043
- Synthesis of aquatic studies: https://irma.nps.gov/DataStore/Reference/Profile/593327
- Landcover data: https://irma.nps.gov/DataStore/Reference/Profile/2166993
- Vernal pool assessment: https://irma.nps.gov/DataStore/Reference/Profile/2193176
- Hydrographic and impairment statistics database: https://irma.nps.gov/DataStore/Reference/Profile/2248296
- Wetlands map viewer: https://www.mcgi.state.mi.us/wetlands/mcgiMap.html
- Aquatic monitoring plan by Loope (2004): https://irma.nps.gov/DataStore/Reference/Profile/2280118

Glacial Features

During the Pleistocene Epoch (2.6 million to 11,700 years ago; see table 1), climate alternated between glacials (ice ages) and interglacials (relatively warm periods similar to modern climate). Glacial ice covered Michigan during the major North American glacials of the Pleistocene Epoch. The most recent glacial is called the Wisconsinan. The glacial deposits and history of Wisconsin have been described by Black (1974). Climate and ice sheet fluctuations within a glacial are called stages. Successive glacial advances and retreats, responding to fluctuations of Earth's climate, are known as glacial stages (colder climate and glacial advance) and interglacial stages (warmer climate and glacial retreat), respectively.

The Great Lakes (Superior, Michigan, Huron, Erie, and Ontario) all occupy basins carved by glaciers. The development of Lake Superior, however, differs from the other Great Lakes because of its association with the Midcontinent Rift System. The rift (see "Geologic Setting and History" section) forms a permanent zone of weakness in Earth's crust. As part of the ancient rift structure, Lake Superior was already a basin prior to glaciation. The preexisting basin funneled glacial ice (Superior lobe) causing further erosion to scour the Lake Superior basin, making it the deepest of the Great Lakes (Thornberry-Ehrlich 2010). For the other Great Lakes, preexisting valleys formed during extensive erosion from about 66.0 million to 2.6 million years ago (so-called Tertiary time), particularly in areas where easily eroded shale (as opposed to neighboring sandstone and limestone; see table 2) was at the surface, and the Pleistocene glaciers followed suit (Kevin Kincare, US Geological Survey, geologist, written communication, 5 October 2021).

The evolution of the landscape at the lakeshore is intimately tied to the glacial history of the area. Repeated glacials scoured and reshaped the landscape of the northern United States, including the lakeshore, when massive ice sheets advanced from the Arctic (see fig. 10). Each subsequent glacial overprinted or obliterated the record of the previous glacial. Several substages of the Wisconsinan glacial stage, including the Two Rivers substage and the Marquette substage, affected glacial features at the lakeshore. During one of the last substages of the Wisconsinan glacial stage (about 12,000 years before present), the area was "wiped clean" by retreating glaciers, with a brief readvancement of glacial lobes (e.g., Marquette lobe) in northern Michigan around 10,000 years ago (Fisher and Whitman 1999; Hunt et al. 2008). Most glacial terrain within the lakeshore formed during a 300–500-year period as the last retreating ice margin confined eastward-flowing meltwater streams against the Munising terminal moraine to the south (Blewett 1994). Streams carved an intricate series of channels, which are now preserved as terraces throughout the lakeshore's uplands (Legg and Anderton 2010). A series of glacial lakes (e.g., glacial lakes Minong and Algonquin) formed at the retreating front of the glaciers. Large rivers at that time deposited vast sheets of outwash over the area. Glacial deposits extensively mantle the underlying bedrock formations throughout the national lakeshore (see "Pictured Rocks" section); bedrock is only visible at the surface where it crops out as cliffs along the shoreline (Thornberry-Ehrlich 2010).

Glaciers deposit a variety of sediments and create distinctive landforms (fig. 24). The two major categories of glacial features at the lakeshore are (1) those created by glacial ice, and (2) those created by glacial meltwater, either "glaciofluvial" (deposited by rivers flowing beneath or out of glaciers) or "glaciolacustrine" (deposited in lakes near glaciers). Figure 24 provides schematic illustrations of these features. Features created by glacial ice include till, moraines, drumlins, kettles, grooves, striations, roches moutonnées, and glacial erratics. Glaciofluvial and glaciolacustrine features include kames; eskers; braided streams; glacial drainage channels; and outwash fans, deltas, or plains. Such features are significant in the mapped area. VanderMeer et al. (2020) provided detailed glacial histories and feature descriptions for the lakeshore area.

Features of Glacial Ice

Mapped features that are evidence of past glacial movement include drumlins, push moraines, and associated ice extents. Drumlins are elongated linear hills that formed when a glacier flowed over a mass of sediment (fig. 25). They are mapped south of the lakeshore boundary (map unit **Qdr** and "long axis of drumlin" in the "Glacial Feature Lines" layer of the GRI GIS data; see table 3). Primarily oriented northwest–southeast, drumlins indicate that the direction of glacial movement in the area was toward the southeast (VanderMeer et al. 2020). The stacked push moraine (**Qpm**) formed as the glacier shoved preexisting sediment (older outwash) into a mound coincident with the ice-extent line ("limit of ice extent/margin" in the "Glacial Feature Lines" layer of the GRI GIS data). Stacked push moraines mark where the glacier stagnated and began to retreat; push moraines consist of formerly stratified sediments that were "pushed" and deformed (fig. 26; VanderMeer et al. 2020).

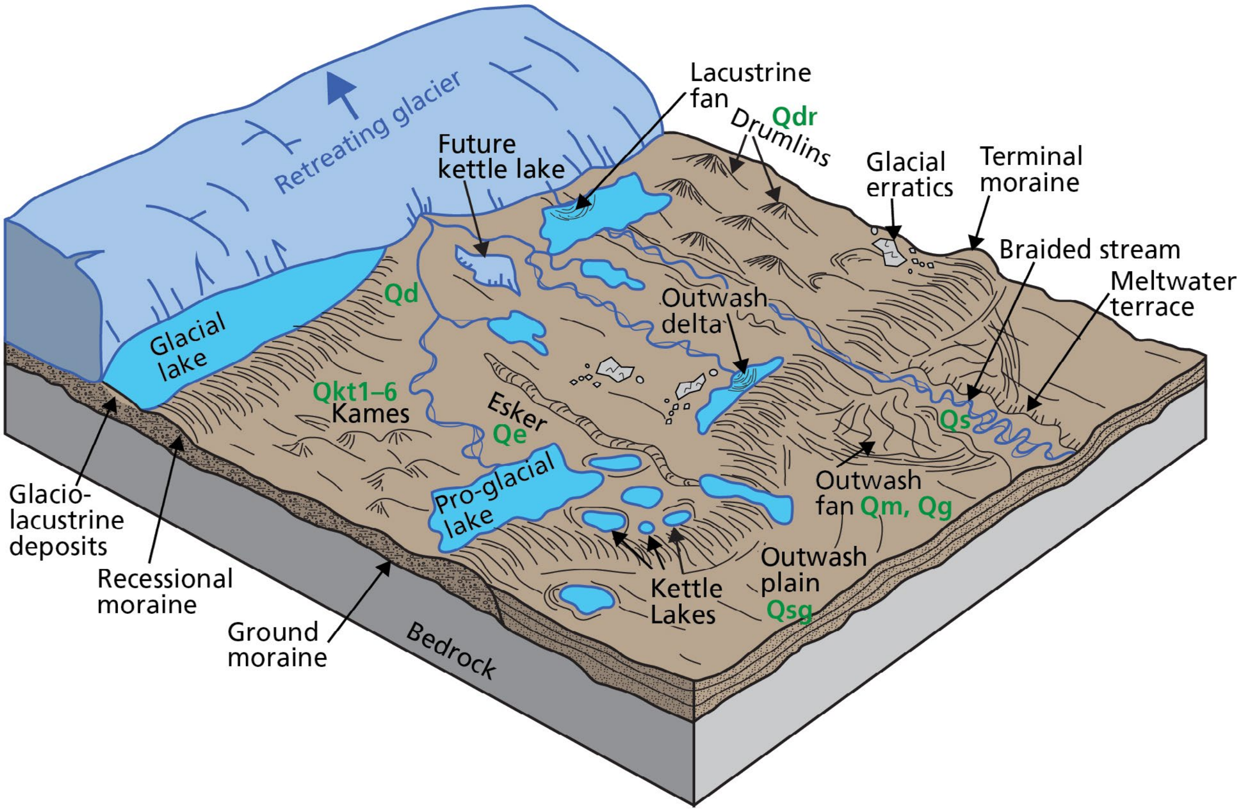


Figure 24. Schematic diagram of glacial features.
Not every glacially altered landscape contains all of these features or deposits. Prominent features and deposits within the lakeshore are labeled and include lacustrine fans, drumlins, glacial erratics, glaciofluvial deposits, outwash fans, outwash deltas, glaciolacustrine deposits, glacial grooves, striations, and kames (terraces). Where possible, geologic map unit symbols are listed in green text. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

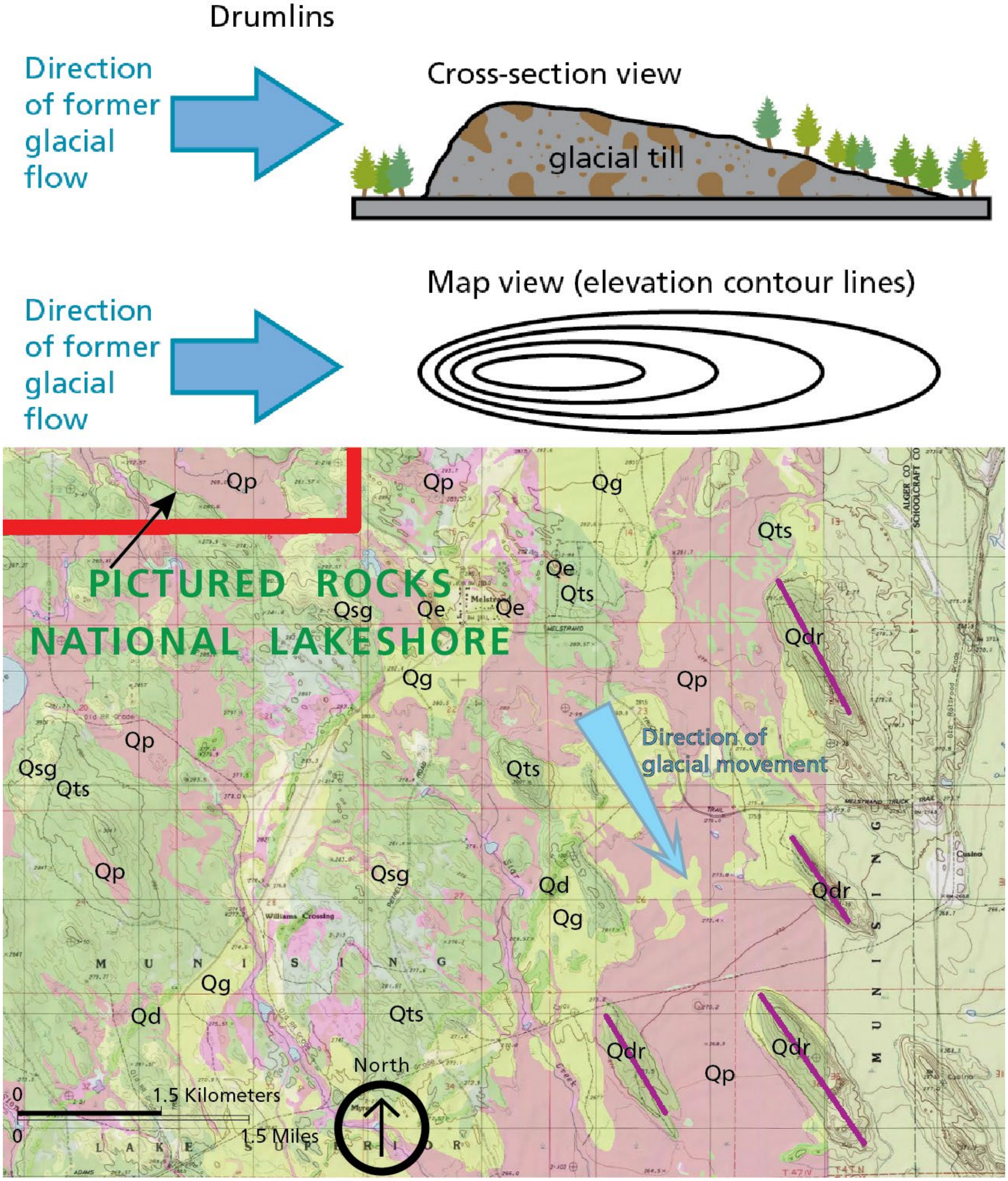


Figure 25. Schematic diagram and map of drumlins near Pictured Rocks National Lakeshore. Drumlins are low, smoothly rounded, elongate oval hills that are formed by the movement of a glacier atop previously deposited glacial till. The long axis of the drumlin is parallel to the direction of glacial ice movement. Drumlin locations are indicated in the GRI GIS data (map unit Qdr and part of the "Glacial Feature Lines" layer); they occur just south of the lakeshore boundary (bold red line in the northwest corner of the map). This topographic map is marked with purple lines indicating the long axis of several drumlins. The axes are oriented north-northwest to south-southeast, parallel with the glacial movement that formed them. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with US Geological Survey topographic coverage available from ESRI online.

Figure 26. Photograph of a push moraine at Pictured Rocks National Lakeshore.
This feature (Qpm) formed as a readvancing ice sheet pushed preexisting layered glacial outwash into a deformed mound. The swirls are deformed bedded sand. Photograph by Alan Kehew presented as photo 2 in the GRI GIS data (VanderMeer et al. 2020).

Other glacial scour features that are not part of the GRI GIS data are tunnel channels, glacial grooves, and striations. These types of features also record the direction of ice movement as rocks entrained at the base of a glacier are scraped over the underlying bedrock. Tunnel channels are continuations of deep grooves in the floor of Lake Superior. The Miners River currently occupies a tunnel channel. These features are the subject of much scientific interest (Thornberry-Ehrlich 2010).

Features deposited by moving ice, and captured in the GRI GIS data, include thin sediment above bedrock (surficial geologic map unit **Qts**), diamicton ridge (**Qd**), and stacked push moraine (**Qpm**). Glacial till (a mixed assortment of sediments deposited directly from glacial ice) mantles much of the bedrock beneath and surrounding Lake Superior itself.

Features of Glacial Meltwater

Glacial deposits in the lakeshore area include those created by glacial meltwater in rivers or lakes. Eskers (**Qe**), or sinuous ridges of stratified sediment deposited by streams flowing through meltwater tunnels or subglacial streams, formed within the glacier itself. Most of the glacial deposits at the lakeshore stemmed from the environment of a melting glacier ice-margin in the form of kame terraces (**Qkt1–6**), meltwater sluiceway (**Qs**), outwash (**Qsg**), and outwash fan complexes (**Qg** and **Qm**; VanderMeer et al. 2020). As streams were rushing away from the melting ice, large (<1 m [3 ft] across) potholes formed as cobbles were swirled around in eddies, scouring the underlying surface during extreme flow events. Potholes are visible along Miners River and Sable Creek (at Sable Falls).

Within the outwash fans spreading away from the melting glacier, commonly blocks of ice would be stranded, surrounded and buried by outwash sediments. When the ice block eventually melts, the sediment collapses and a depression is left (a kettle), which may or may not contain water. Kettles are part of the hummocky, bumpy, irregular land surface of the lakeshore (VanderMeer et al. 2020).

Glacial Lake Stages and Holocene Lake-Level History

When glacial ice retreated from the Lake Superior basin for the last time, approximately10,000 years ago, lake levels fluctuated dramatically as a function of several factors: climate, isostatic rebound, outlet incision, and sedimentation (Blewett 2006). When various outlets were first exposed by deglaciation, lake levels dropped, and then rose again as the outlets were abandoned due to isostatic rebound of the basin; the land lifted too high to act as a drainage outlet (Pranger 2005). A series of glacial lakes formed landward of the large continental glacier during its Pleistocene retreat from northern Michigan. Following the final glacial ice retreat, water from the glacial lakes drained through Lake Ontario over approximately 1,000 years as melting ice revealed progressively lower outlets. This left many remnants of past lake levels preserved and a complicated record of past shorelines on highlands (or islands). As mentioned in the "Geologic Setting and History" section, at the lakeshore, only the Nipissing phase shoreline is clearly preserved, at approximately 12 m (40 ft) higher than the current Lake Superior water level (VanderMeer et al. 2020). Some maps also present some Algonquin level shorelines (Martin 1957), but these were not confirmed by recent mapping at the lakeshore.

At its highest about 5,000 cal yr BP, the Nipissing phase level was 15 m (50 ft) higher than the present lake level (Larsen and Schaetzel 2001). This stage left wave-cut cliffs, caves, and other shoreline features perched above the present Lake Superior shoreline. Infilling of Chapel beach occurred at the height of the Nipissing phase. The longshore currents of this phase washed sand across stream outlets, effectively impounding several small lakes including Chapel Lake (Thornberry-Ehrlich 2010). Sand Point contains surficial deposits from the Nipissing phase (sourced from the "punky" sandstone of the Miners Castle Member of the Munising Formation; geologic map unit **Cm**). Locally, transgressions occurred because isostatic rebound allowed Earth's crust to rise. Rebound has continued to occur ever since the last glacial ice finally melted off. Rebound at Lake Superior's outlet at Saint Marys River separated it topographically from the lower lakes approximately 2,280 years ago (Farrand and Drexler 1985). At this time, the proto-Lake Superior approached its modern elevation.

Geologic Hazards

A geologic hazard, or geohazard, is a naturally occurring, dynamic geologic process capable of causing damage, loss of property, and/or injury and loss of life. Hazardous geologic processes can happen slowly over days or years, or they may have a sudden onset occurring in seconds or minutes. The risk associated with a geologic hazard may be exacerbated by human activities (e.g., building trails beneath unstable slopes). Risk is the probability of occurrence 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 also Holmes et al. 2013). The most common geologic hazards at the lakeshore are associated with both bedrock and unconsolidated slopes and their threats to visitor safety.

Slope Movements

Slope movements are the downslope transfer of soil, regolith, and/or rock under the influence of gravity. Slopes become unstable when downward forces exceed the strength of the material composing the slope (Anderson 2003). Soil creep, rockfalls, debris flows, and avalanches are common types of slope movements. These processes and the resultant deposits are also known as "mass wasting" and commonly grouped as "landslides." Slope movements occur on time scales ranging from seconds to years. Figure 27 shows schematic illustrations of slope movements. Slope movements create geologic hazards and associated risk throughout the National Park System. The type of slope movement in a particular area depends on the type of geologic material, the nature and steepness of the slope, and other factors such as vegetation, the presence of seeps and springs, and/or exposure to erosion by moving water (fig. 27).

Slope movements at the lakeshore include dramatic shoreline bluff rockfall wherein large blocks of bedrock suddenly tumble down the cliff face to litter the shoreline. Also, slumping takes place where masses of unconsolidated material slide downslope (National Park Service 2016). The bedrock exposed along the shoreline is prone to topple, block fall, slides, and/or collapse of sea arches and stacks (fig. 28), whereas the slopes of unconsolidated material such as those at Grand Sable Dunes are prone to translational and rotational slides, slumps, debris flows, and creep (see fig. 27).

Hundreds of rockfalls take place at the lakeshore every year; most are not very noticeable, but a significant event tends to occur about every five to seven years (Thornberry-Ehrlich 2010). Lakeshore staff members note that slope movements are most common in spring (National Park Service 2016), and they are noticing an increase in the frequency of rock formation collapses and erosion (Bruce Leutscher, Pictured Rocks National Lakeshore, chief of Science and Resource Stewardship, conference call, 29 July 2020).

Slope movements are natural elements of shoreline and landscape evolution. However, some slope movements

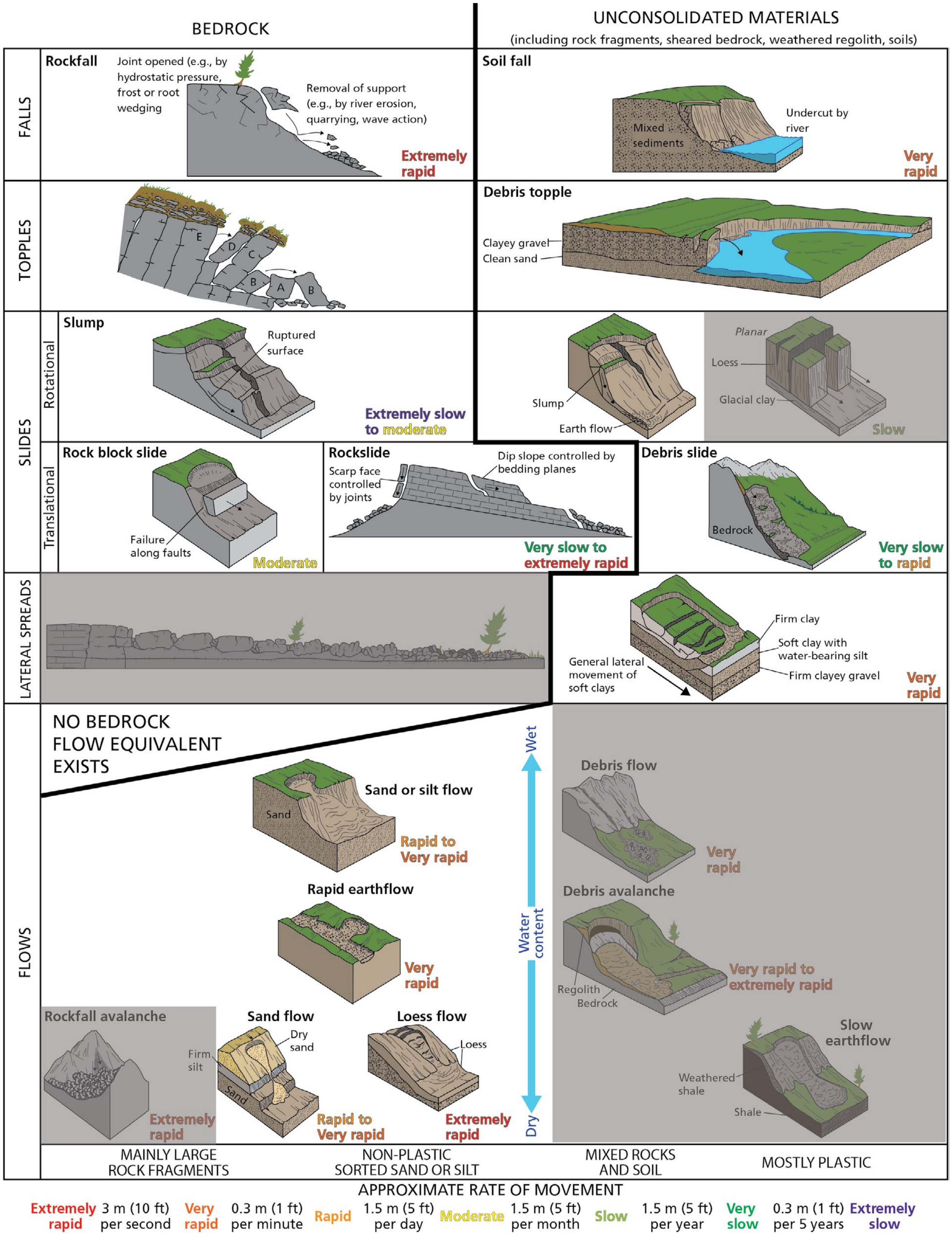


Figure 27. Schematic illustrations of slope movements.
Different categories of slope movement are defined by material type, nature of the movement, rate of movement, and moisture content. The most significant slope movements in the lakeshore include rockfall, soil fall, and sand flows. Gray-shaded categories are unlikely to occur in the lakeshore. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Varnes (1978, figure 4.33 and information therein).

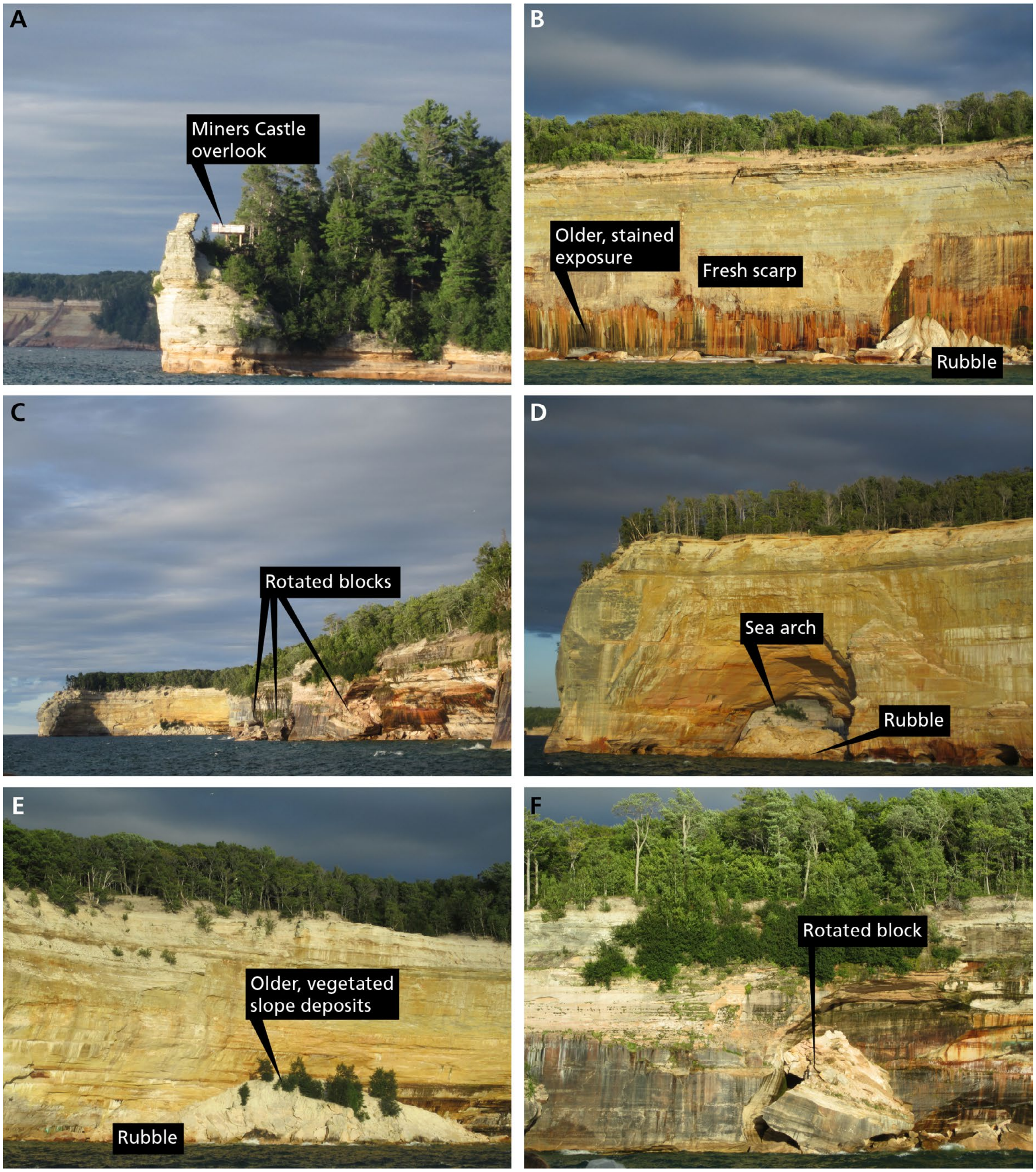


Figure 28. Photographs of active slope processes.
In addition to soft-sediment slope processes (unconsolidated materials falls, topples, slides, and flows listed in fig. 27), the steep bedrock cliffs at the lakeshore are prone to slope processes as their surfaces are battered by wave action, frost wedging, and root wedging. Because the exposure is so excellent, the slope deposits are clearly distinguishable along the shoreline. (A) Miners Castle overlook sits atop a crumbling outcrop of the Munising Formation. (B) An unstained scarp indicates a very recent slope failure where blocks of the cliff face spalled into the lake below. (C) Entire layered blocks of rock are wedged from the cliff face and will eventually tumble into the lake below. (D) Rockfall and collapse are responsible for forming the famous sea arches along the lakeshore. (E) Slope deposits may be intermittently stable—long enough to support limited vegetation. These types of deposits protect the adjacent slopes from direct contact with the lake's wave action. (F) A rotated block below a vegetated slope can still be traced to its original position as part of the cliff face. Photographs by Trista L. Thornberry-Ehrlich (Colorado State University) taken in summer 2009.

threaten infrastructure such as trails and overlooks, cultural resources at the lakeshore, and visitor safety on land and in the water (National Park Service 2016). The areas most affected are trails near the cliffs; observation points near places prone to erosion; and paddling destinations near cliffs such as under arches, into sea caves, and near other unstable formations.

Infrastructure Impacts

Along the sandstone-rimmed shoreline cliffs (geologic map units **Yj**, **Cm**, and **Ct**), slope movement hazards pose risks to infrastructure integrity and visitor safety. Blocks of rock frequently spall off the cliff faces as a result of wave activity and weathering, primarily along joints and fractures. The Munising Formation (**Cm**) has friable layers that are relatively weak and prone to erosion. For instance, one of the two turrets at Miners Castle (a notable landmark in the lakeshore) collapsed in spring 2006 (see fig. 16), another large block fall occurred near Indian Head (year unknown), and visitors captured photographs of falls between Miners Castle and Mosquito beach in 2019 and 2021 (Thornberry-Ehrlich 2010; Navarro 2021). Failure of the steep bedrock cliffs can be hazardous, applying to both visitors hiking along the top edge and those floating below looking up from Lake Superior. Particularly hazardous areas, such as those with visible cracks, loose material, or overhangs, could be cordoned off to reduce some visitor safety concerns, but the potential remains for the cliffs to break and crack suddenly.

Because of rapid slope movements such as rockfall, viewing platforms may disappear quickly in particularly dynamic settings (Bruce Leutscher, Pictured Rocks National Lakeshore, chief of Science and Resource Stewardship, conference call, 29 July 2020). Many overlooks are situated on high rock ledges where the bedrock is undercut and naturally fractured. While walking along the base of the bluffs at the Grand Sable banks, people noted seeing a “shipwreck” emerging offshore that was revealed to be the remains of the viewing platform that had tumbled into the water (Walt Loope, US Geological Survey, retired research ecologist, conference call, 29 July 2020). The Miners Falls overlook and trail had to be moved because of slumping and slope collapse associated with an old fault that provided a source of weakness in the rock (Walt Loope, US Geological Survey, retired research ecologist, conference call, 29 July 2020). As of 2020, the existing platform is still on jointed-bedrock exposures and could slump or collapse again; a project is currently being researched to move the overlook downslope. National Park Service (2016) noted the viewing platform needs to be enlarged or improved. This may be problematic given all the exposed bedrock there (Bruce Leutscher, Pictured Rocks National Lakeshore, chief of Science and Resource Stewardship, conference call, 29 July 2020). NPS Geologic Resources Division geomorphologists can provide technical assistance (https://www.nps.gov/orgs/1088/index.htm).

Unconsolidated Sediment Collapse

The semi-consolidated deposits (**Qkt1**) at the Grand Sable banks are naturally prone to erosion, slumping, and sloughing. Though prohibited, visitors have dug cavities into the banks. Collapse of these temporary excavations can be fatal as happened to a boy in 2006 when a tunnel dug into the banks buried him (Thornberry-Ehrlich 2010; Walt Loope, US Geological Survey, retired research ecologist, conference call, 29 July 2020). When failures occur, visitor access points are blocked until an angle of repose is reestablished and the banks are more or less stable (Bruce Leutscher, Pictured Rocks National Lakeshore, chief of Science and Resource Stewardship, conference call, 29 July 2020).

Waterfall Hazards

Waterfalls form in part by slope movements and pose public safety issues, including rockfall, slippery surfaces, and drownings. Waterfall numbers vary and some waterfalls are seasonal, but about 20 waterfalls occur within the lakeshore, most of which are accessible by trails. Dolomitic sandstone of the Trempealeau Formation (**Ct**) forms a resistant cap rock along the top edge of the Pictured Rocks cliffs (Milstein 1987) and the sites of many waterfalls (e.g., Bridalveil Falls, Miners Falls, Spray Falls, and Chapel Falls) that flow over the cap rock in dramatic sprays to the lake below (see fig. 13 and inside cover; National Park Service 2016). Visitors are no longer allowed to walk behind Munising Falls (Thornberry-Ehrlich 2010).

Paddling Risks

Increased visitation and kayak activity have caused concern for resource managers because paddlers in small pods of watercraft have the ability to stop right below the cliffs. Sea kayaking has become a multimillion-dollar business at the lakeshore, and despite required hazard warnings for authorization, kayaks are often spotted in dangerous settings (Bruce Leutscher, Pictured Rocks National Lakeshore, chief of Science and Resource Stewardship, conference call, 29 July 2020). In 2019, a video emerged of a group of kayakers narrowly avoiding being struck by falling rocks (John Yellich, Michigan Geological Survey, chief geologist, conference call, 29 July 2020; Navarro 2021).

Erosion

Erosion is the action of surface processes (such as flowing water or blowing wind) that removes soil, rock, or dissolved material from one location to be transported to another location. This is not to be confused with weathering, which is in situ and involves no movement. Erosion is commonly considered a loss of material and a degradation of something. For example, shoreline erosion may involve the loss of beaches. This process is active in some areas of the lakeshore (see discussion in "Lake Superior Shoreline" section).

Erosion was listed as a specific threat to trails, including the North Country National Scenic Trail (NCNST) at the lakeshore by National Park Service (2016). The NCNST is the longest in the National Trails System, stretching 7,560 km (4,700 mi) across eight states from North Dakota to Vermont (North Country Trail Association 2021), including 67.9 km (42.2 mi) along the length of the lakeshore. Trails are commonly situated where they are easiest to build, not necessarily where is best for the landscape (Bruce Leutscher, Pictured Rocks National Lakeshore, chief of Science and Resource Stewardship, conference call, 29 July 2020). Many segments of this trail have required rerouting, some on a nearly annual basis. The trail follows right along the edge of the bluffs.

Erosion is exacerbated by visitor use in some areas. Social trails result in adverse resource impacts. A social trail up the side of a dune at Sable Creek degraded stabilizing vegetation and caused a sand island to form within the nearby stream channel as sand washed downslope (fig. 29; Thornberry-Ehrlich 2010; National Park Service 2016). If the dune were to suddenly slump, sand may impound the stream completely forming a lake (Thornberry-Ehrlich 2010). The National Park Service has invested in infrastructure to maintain visitor access while deterring the creation of social trails and allowing slope processes to return to natural conditions (Thornberry-Ehrlich 2010).

Water-saturated soils exacerbate erosion along the Munising Falls trail. Resource managers feel the entire trail needs to be rerouted to a more stable location; it currently runs through a narrow valley, and sections of the trail are moving. However, the trail is also part of the Schoolcraft Furnace Site, which is on the National Register of Historic Places. This situation limits what alterations are permitted. The request for a new site design is ongoing as of 2022 (Bruce Leutscher and Laura Waller, Pictured Rocks National Lakeshore, chiefs of Science and Resource Stewardship; conference call, 29 July 2020, and written communication, 9 September 2021, respectively).

Erosion at Log Slide overlook is a threat to resource protection, visitor safety, and infrastructure. Visitors frequently create social trails to access the shoreline from the overlook. Their social-trail activity dislodges or removes the armoring stones that are left on the sand surface following wind erosion (i.e., the wind removes the finer sand from around these stones). Armoring stones naturally act as temporary bulwarks against further erosion. When the armoring stones are removed, erosion is exacerbated, creating notches 3 to 6 m (10 to 20 ft) deep in the face of the banks. In 2016, the National Park Service noted the need to redesign the Log Slide overlook to address visitor safety and structural issues of the viewing platform. Shortly thereafter, winter storms and erosion caused the platform to break off and slide down the face of the dune. As of July 2020, the viewing platform has not been rebuilt.

Roads and trails may divert and funnel runoff, causing erosion along and under their paths (Bruce Leutscher, Pictured Rocks National Lakeshore, chief of Science and Resource Stewardship, conference call, 29 July 2020). This process is forcing the relocation of the county road inside the lakeshore boundary. Erosion has undermined and even removed some sections of the old road (Thornberry-Ehrlich 2010).

Seismicity

Seismic activity (earth shaking) may occur when rocks suddenly move along a fault, releasing accumulated energy and causing earthquakes (see Braile 2009). Earthquake intensity or magnitude ranges from imperceptible by humans to total destruction of developed areas and alteration of the landscape. The "Richter magnitude" is a measure of the energy released by an earthquake. Earthquakes can damage site infrastructure directly or trigger other hazards such as slope movements on the bluffs above the river that may impact site resources, infrastructure, or visitor safety.

The lakeshore is not located near an active seismic zone. US Geological Survey earthquake probability maps indicate an almost 0% probability of a magnitude-5.0 or greater earthquake occurring in the next 100 years at the lakeshore (fig. 30; Petersen et al. 2008). Since melting of the last glacial-ice load, isostatic rebound of the land surface may cause small earthquakes to occur occasionally at the lakeshore as Earth's crust adjusts to the lack of ice weighing it down; however, most of these events range in magnitude between 2 and 3 and are too minor to be felt by humans (Thornberry-Ehrlich 2010).

Figure 29. Photographs of trail rehabilitation projects and a social trail up the side of a dune. (A) Social trail use has created an unstable (de-vegetated) slope along the side of an active dune. The lakeshore staff have attempted to use signage to discourage access. (B, C, and D) The trail down to the base of the Grand Sable banks along Sable Creek was the subject of significant restoration work as erosion, stream channel migration, and overuse threatened several stretches. (E) Natural stream meandering and erosion causes treefall along stretches of lakeshore streams. This can expose more sediment to the adjacent stream channel. Photographs by Trista L. Thornberry-Ehrlich (Colorado State University) taken in summer 2009.

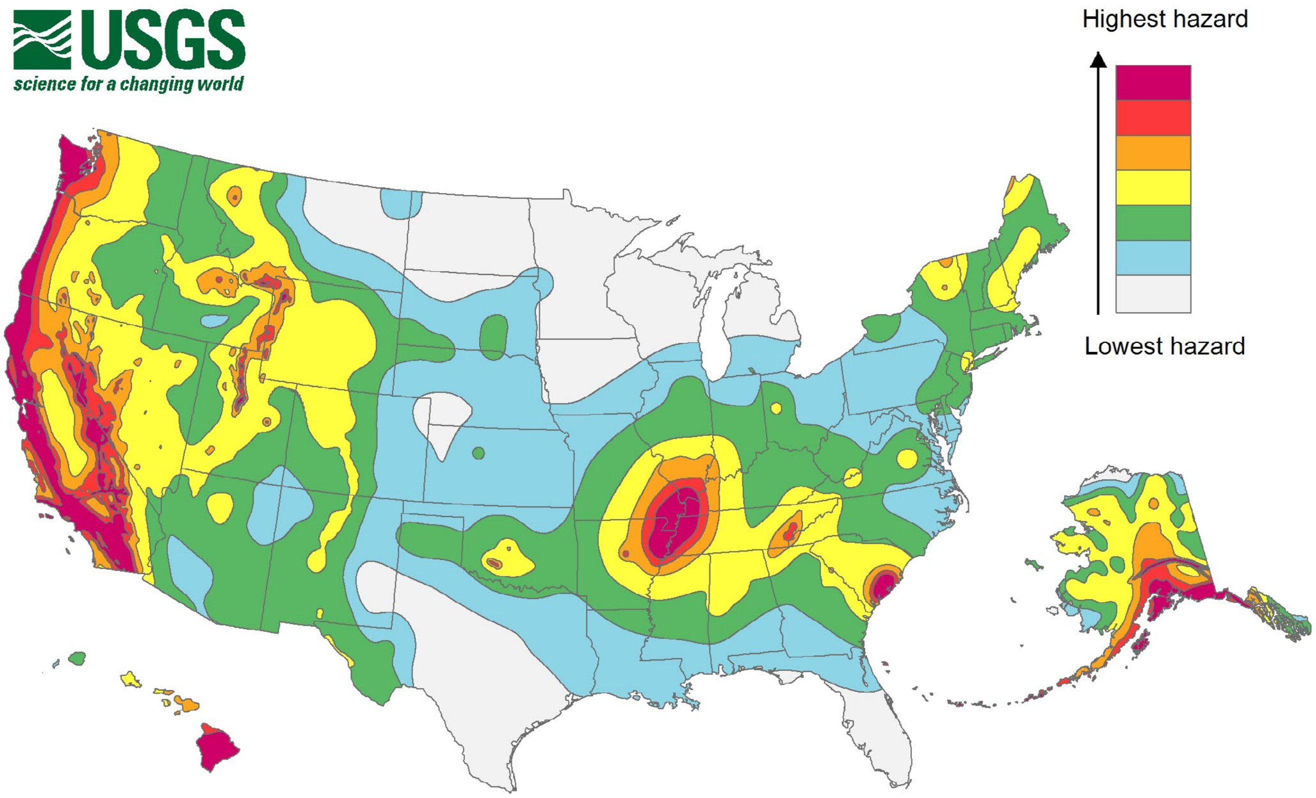


Figure 30. Seismic hazards map.
The map shows the degree of earthquake hazard across the United States based on the 2018 update of the National Seismic Hazard Model (https://www.usgs.gov/programs/earthquake-hazards/science/introduction-national-seismic-hazard-maps). Locally, the hazard may be greater than shown because site geology may amplify ground motions. Northern Michigan is not near a known active seismic zone and has a very low probability of seismicity. Graphic by the US Geological Survey.

Geohazards Management

A monitoring plan for geohazards at the lakeshore was listed as a medium-priority data need in the lakeshore's foundation document (National Park Service 2016). National Park Service (2016) also identified the following action items related to geomorphic processes and associated features:

- Increase interpretation and education related to the continuation of natural processes, geohazards, and climate change. These discussions could be used as a springboard to further discuss sustainability.
- Carefully consider potential geohazards or erosion processes when planning new or improved infrastructure (i.e., trails, roads, campsites).
- Maintain investment in popular, well-situated trails and overlooks, striving for naturalness and minimum impacts.
- Continue working with a National Park Service geomorphologist to develop trail standards for distance from the cliff edge in areas with an identified geohazard.

The surficial geologic data (VanderMeer et al. 2020) compiled as part of the GRI GIS data provide a good starting point when planning to install or relocate trails and other visitor use facilities. In addition, the following websites and publications could provide information for developing a slope management plan including monitoring and mitigation options at the lakeshore: Wieczorek and Snyder (2009); Highland and Bobrowsky (2008); the US Geological Survey landslides website (http://landslides.usgs.gov/); and the NPS Geohazards website (https://www.nps.gov/subjects/geohazards/index.htm). In the *Geological Monitoring* chapter about slope movements, Wieczorek and Snyder (2009) provided guidance and described five vital signs for understanding and monitoring slope movements:

(1) types of landslides, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessment of landslide hazards and risks.

Climate Change

Global climate models predict the Great Lakes region to experience warmer, stormier, and drier climate conditions into the next century; summer temperatures in the region are projected to rise by at least 3°C (5°F) by 2100 (Pendleton et al. 2007; Great Lakes Network 2007; Melillo et al. 2014). A warmer, drier climate may result in more evaporation, less recharge, higher wind speeds (see "Aeolian Features and Processes" section), and ultimately lower lake levels and warmer water. Lake level is virtually never constant with seasonal fluctuations, but data from climate models suggest overall Lake Superior levels could fall at a rate of 8 mm/year (0.3 in/year) by 2090 (US Global Change Research Program 2000; Pendleton et al. 2007; Great Lakes Network 2013).

Although climate change planning is beyond the scope of the GRI program, climate change is included in this GRI report because of its relevance to geologic features and processes. Lakeshore managers are directed to the NPS Climate Change Response Program to address issues related to climate change (https://www.nps.gov/orgs/ccrp/index.htm).

Climate change may contribute to increased erosion at the lakeshore, specifically cliff and shoreline erosion. Lakeshore staff have noted spring and fall periods are experiencing more fluctuations in temperatures (National Park Service 2016). These changes will result (and likely already are resulting) in more frequent and prevalent freeze-thaw cycles. A freeze-thaw cycle occurs when liquid water flows through fractures in the rock and upon freezing, expands and forces the rocks on either side of the fracture further apart as a wedge. More frequent and prevalent freeze-thaw cycles will, therefore, exacerbate cliff erosion. Despite recent exceptions to the trend (e.g., the cold winter of 2013–2014), the warmer and drier predicted climate will lead to a decrease in area and duration of winter ice cover. Winter ice reduces surface-water evaporation and protects the shorelines from winter storms; decreased ice cover will allow the impacts of erosive wave energy to increase. Increased severity and frequency of rain and winter storms will increase erosion on slopes as well (National Park Service 2016). Predicted climate change will also concentrate visitor use during certain times of the year, placing more demands on the resources and causing erosion-related impacts (National Park Service 2016).

A climate change inventory is listed as a high-priority data need in National Park Service (2016). Melillo et al. (2014) provided a comprehensive summary of climate-change observations, impacts, and predictions for the United States. They also presented response strategies and guidance for mitigating climate-change impacts. The strategy for adaptation and mitigation responses to climate change at the lakeshore is evolving and ongoing (Climate Change Response Program 2012). Climate change management strategies are part of park planning and include monitoring and assessing predicted and actual impacts of climate change (National Park Service 2011). The lakeshore's website details specific and multidisciplinary climate change concerns: https://www.nps.gov/piro/learn/nature/climate-change-impacts.htm#CP_JUMP_3227743. Historical and projected climate change trends are available at https://irma.nps.gov/Datastore/Reference/Profile/2266988. The lakeshore's weather and climate inventory is at https://irma.nps.gov/Datastore/Reference/Profile/649242.

Disturbed Lands

Disturbed lands are those park lands where the natural conditions and processes have been directly impacted by development, including facilities, mining, military bases, roads, dams, and abandoned campgrounds; agricultural activities such as farming, grazing, timber harvest, and abandoned irrigation ditches; overuse; or inappropriate use. Restoration returns a site, watershed, or landscape to some previous condition, commonly some desirable historic baseline. Usually, lands disturbed by natural phenomena such as landslides, earthquakes, floods, and fires are not considered for restoration unless influenced by human activities.

The GRI GIS data for the lakeshore contain map units that represent disturbed lands: disturbed land, gravel and/or sand pit (**Qdl**) or "pit" on the map by Vandermeer et al. (2020). These features are active or recently active excavation sites for sand and/or gravel that are large enough to be mapped at a scale of 1:24,000 (VanderMeer et al. 2020). Current lakeshore policy is to leave these disturbed sites alone (particularly in wilderness areas) and allow vegetation and weathering to naturally reclaim the areas. As part of the IBZ legislation, landowners (State of Michigan or Hancock Forest) can quarry one gravel pit per 16 ha (40 ac; Bruce Leutscher, Pictured Rocks National Lakeshore, chief of Science and Resource Stewardship, conference call, 29 July 2020). Recent mining for sand occurred along the lakeshore's edge for local fill and roadway construction (H-58 state highway). These sites are not currently being considered for reclamation. Some access roads may be paved at the lakeshore (e.g., in the Chapel/Mosquito area) because gravel is dusty, and landowners want paved roads. The potential source for gravel could be new quarries in the IBZ (Thornberry-Ehrlich 2010;

Bruce Leutscher, Pictured Rocks National Lakeshore, chief of Science and Resource Stewardship, conference call, 29 July 2020).

The lakeshore has a long history of human use. As detailed in the "Geologic Significance and Connections" section, land use ranged from homesteading, logging, and fishing camps. Other disturbed lands within the lakeshore (including the IBZ) include homesteads, farm fields, old logging roads, earthen and concrete dams, dump sites, and orchards (Thornberry-Ehrlich 2010; National Park Service 2016). Many of the "disturbed" lands within the lakeshore are now considered cultural resources. Some historic orchards are slated to be maintained (National Park Service 2016). Structures without cultural significance mostly are being allowed to reach a state of equilibrium with the natural environment (Thornberry-Ehrlich 2010).

Extensive logging took place between the mid-1800s and 1940. Forests are recovering, but species targeted for restoration (primarily American beech, [*Fagus grandifolia*] which was heavily impacted by beech bark disease) are still in lower abundance than they have been historically (Thornberry-Ehrlich 2010; Laura Waller, Pictured Rocks National Lakeshore, chief of Science and Resource Stewardship, written communication, 9 September 2021). The IBZ, which covers at least half of the lakeshore area, is permitted for commercial logging with locations varying annually (Laura Waller, Pictured Rocks National Lakeshore, chief of Science and Resource Stewardship, written communication, 9 September 2021). Logging operations include clearcutting pine tree (e.g., white pine [*Pinus strobus*]) forests and selective harvesting of hardwood areas. Logging activities also involve constructing temporary roads and bridges for access (Thornberry-Ehrlich 2010). Logging is noted in the lakeshore's foundation document as a threat to visual resources (National Park Service 2016).

Coastal beaches and dune areas are particularly vulnerable to degradation from disturbances caused by past logging, heavy visitor use, and exotic vegetation. At nearby Apostle Islands National Lakeshore, restoration strategies include revegetation, removing exotic species, limiting access, and recontouring the land surface (Pranger 2005). Restoration, primarily consisting of planting vegetation, is done where disturbed lands have been created by current and/or past human activities.

Abandoned Mineral Lands

According to the NPS Abandoned Mineral Lands (AML) database (accessed 3 September 2021) and Burghardt et al. (2014), the lakeshore contains two AML features at two sites; these features were not identified as requiring mitigation. An AML site is an area consisting of AML features logically grouped by past ownership or geography. AML features are elements of a site such as adits, open pits, mining structures, and waste rock piles; a complete list is provided by Burghardt et al. (2014, Appendix A). AML features present a variety of resource management issues for visitor and staff safety; air, water, and soil quality; and habitat for animals. Management of AML features requires an accurate inventory and reporting. All AML features should be recorded in the NPS AML database (the NPS Geologic Resources Division can provide assistance). An accurate inventory can identify human safety hazards and facilitate reclamation and restoration of AML. When appropriate for resource management and visitor safety, features can also present opportunities for interpretation as cultural resources. The NPS AML Program website, https://www.nps.gov/subjects/abandonedminerallands/index.htm, provides further information.

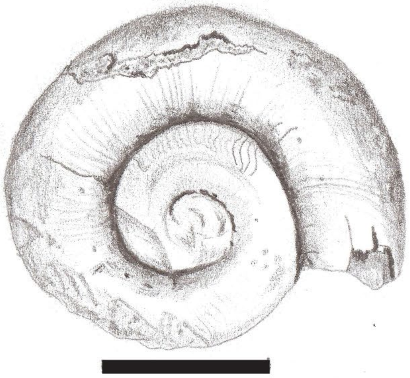
Access to the two AML features within the lakeshore is restricted with wooden fences and railings. One feature is a former gravel pit in the designated wilderness area. Although it presents a scar on the landscape, in keeping with wilderness management policy the site will be allowed to naturally revegetate (Bruce Leutscher, Pictured Rocks National Lakeshore, chief of Science and Resource Stewardship, conference call, 29 July 2020). The second AML feature is a remnant of a large gravel pit. Lakeshore staff are interested in monitoring it, but given its small area within the lakeshore boundary, it is not a management priority (Bruce Leutscher, Pictured Rocks National Lakeshore, chief of Science and Resource Stewardship, conference call, 29 July 2020).

Paleontological Resources 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 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 unconsolidated deposits, museum collections, and cultural contexts such as building stones or archeological resources. As of May 2022, 283 NPS areas had documented paleontological resources in at least one of these contexts.

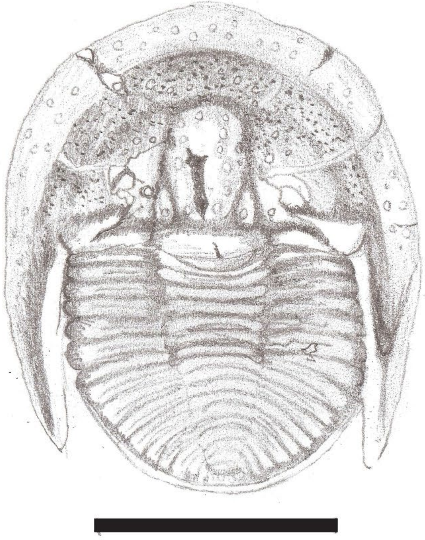
The lakeshore contains Cambrian and Ordovician fossils (fig. 31) and fossils in glacial deposits. Potential exists for younger fossils, and discovery of Pleistocene and Holocene fossils is possible at the lakeshore (Hunt et al. 2008).

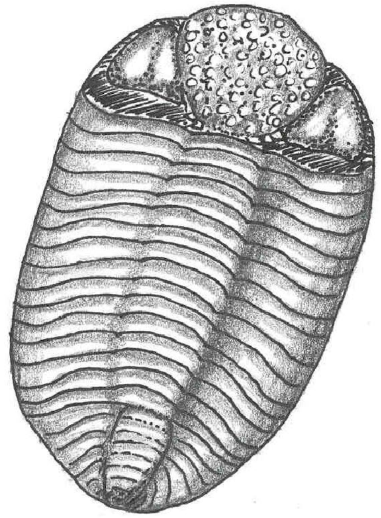
Gastropod *Platystoma*



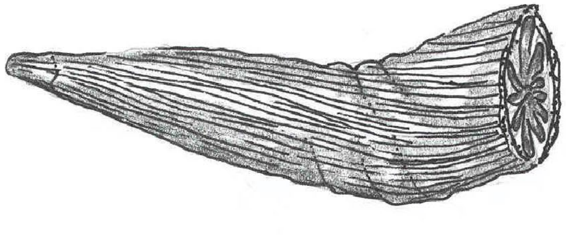
Brachiopod *Howellella*

Trilobite *Cordania*

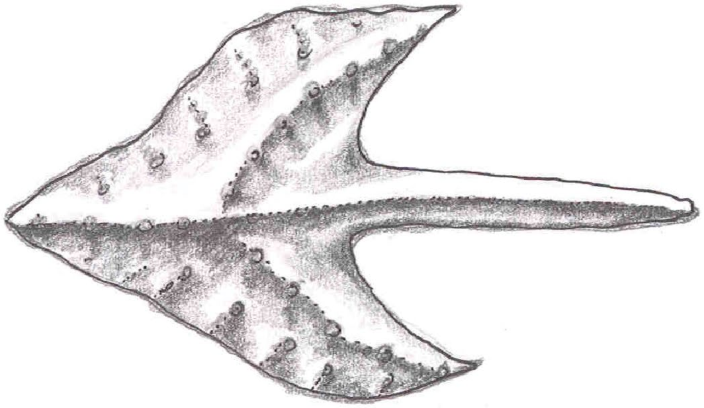




Phacops rana milleri
(trilobite - Mid-Devonian) (4 cm)



Lophophyllum profundum
(horn coral - Pennsylvanian) (5.5 cm)



Ancyrodella
(conodont - Late Devonian) (x 55)

Figure 31. Sketches of fossils.
The limestone, dolomite, and sandstone layers at the lakeshore are fossiliferous. These sketches are representative of some of the fossil types that may be present in the lakeshore's geologic units. Fossils are at risk of burial or degradation by natural and anthropogenic slope processes, as well as theft. Black scale bars represent 1 cm (0.4 in). Sketches by Trista L. Thornberry-Ehrlich (Colorado State University).

As described in Hunt et al. (2008), the collection at the lakeshore includes conodonts, trilobites, and trace fossils. Conodonts were eel like creatures known only from their tooth-like oral elements found in isolation. Trilobite fossils resemble pill bugs. The Au Train Formation (geologic map unit **Oat**) has brachiopods (reminiscent of a clam), hyoliths (conical shells), chitons (flat, armored looking mollusks), monoplacorphorans (mollusk with a single, cap-shaped shell), nautiloids (resemble snails), gastropods (e.g., snails and limpets), trilobites, conodonts, the enigmatic invertebrate *Phosphannulus* (lamp shell), armor of an ostracoderm (armored, jawless) fish, burrows, fecal pellets, and unidentified tubular elements (Oetking 1952; Miller et al. 2006). In the Munising Formation (**Cm**) conodonts, and invertebrate trace fossils (bioturbation) have been found (Haddox and Dott 1990; Miller et al. 2006). Fossils examined by Miller et al. (2006) are of Early Ordovician age whereas those studied by Oetking (1952), primarily mollusks, indicate younger Ordovician deposition. This contributes to the problematic interpretation of the "Trempealeau Formation" (**Ct**) as late Cambrian because the fossils therein are clearly younger (Justin Tweet, National Park Service, paleontologist, written communication, 7 September 2021). Fossils such as horn corals frequently wash up on the lakeshore (GRI conference call participants, conference call, 29 July 2020). Holocene tree stumps, wood, and peat with conifers represent former forest settings (Anderton and Loope 1995; Fisher and Whitman 1999; Loope et al. 2004). Sediment cores from Beaver Lake contain peat and organic material that can be used to determine age; they record deglaciation, vegetation, and climate changes since the last major ice advance (Fisher and Whitman 1998, 1999; Hunt et al. 2008). Fossil pollen from sediment cores at Twelvemile bog near Lake Superior was analyzed to reconstruct the local history of vegetation since the end of the Pleistocene Epoch (Futyma 1987). Davis et al. (1998) also summarized the late Pleistocene–Holocene paleoecological history of the lakeshore from cores of Buck Lake (just outside of the lakeshore) and Spirit Lake as part of their larger study of ecological change throughout the Great Lakes region.

Paleontological Resource Management

All paleontological resources are subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act (see "Geologic Resource Laws, Regulations, and Policies"). The final Department of Interior regulation associated with the act is available on the Federal Register website at https://www.federalregister.gov/; search for Regulation Identification Number 1093-AA16.

A field-based paleontological resource inventory has not been completed at the lakeshore but could provide detailed, site-specific descriptions and resource management recommendations. Field work could be accomplished by establishing a cooperative agreement with one or more of the local natural history museums with paleontological expertise, such as the University of Michigan, Museum of Paleontology (Hunt et al. 2008). The NPS Geologic Resources Division can help advertise, recruit, and provide technical assistance for these positions or potentially use the SIP program (see "Guidance for Resource Management"). Hunt et al. (2008) suggested development of a paleontological resource management plan for in situ fossils and those that may potentially wash onto the shoreline at the national lakeshore and become subjected to "beachcombing."

A variety of publications and resources provide park-specific or servicewide information and paleontological resource management guidance. For example, in the *Geological Monitoring* chapter about paleontological resources, Santucci et al. (2009) described five methods and vital signs for monitoring in situ paleontological resources: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use. Recommendations from Hunt et al. (2008) include the following:

1. Interview and document geoscience specialists with first-hand knowledge of the geological and paleontological resources in the lakeshore.
2. Locate specimens that have already been retrieved and are currently stored in other repositories. Molds of the significant specimens could be made, and their casts could be placed in the lakeshore's museum collection. Scientifically significant material that may be threatened should be stabilized in situ or retrieved and curated into dedicated storage.
3. Encourage staff to observe exposed cliffs, other erosional bedrock, and streams for fossil material while conducting usual duties. Any observations should include photographs using a common item (e.g., pocketknife) for scale. Fossils and their associated geologic context (rock matrix) should then be left in place unless they are subject to imminent degradation by artificially accelerated natural processes or direct human impacts.

Guidance for Resource Management

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

Three Basic Ways to Receive Geologic Resource Management Assistance

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

Technical Assistance Requests for Pictured Rocks National Lakeshore

The following technical assistance requests were active as of July 2020:

- Coastal morphology implications of modifying or removing the Sand Point revetment. A 2012 study determined the shoreline should be allowed to evolve and the revetment should not be removed. The project was revisited, and lakeshore staff provided comments to coastal geomorphologists from the NPS Geologic Resources Division in 2019. As of summer 2020, the project is ongoing and information is still being gathered to address the situation (see "Coastal Issues" section; GRI conference call participants, conference call, 29 July 2020).
- Determining a process to evaluate the stability of geologic units beneath overlooks and trails. As of summer 2020, this project was still ongoing (GRI conference call participants, conference call, 29 July 2020).
- Determining the need and feasibility of reconnecting the delineated wetlands at Sand Point with the waters of Lake Superior. Findings were compiled in a wetland delineation report by Wagner and Shook (2018). According to 29 July 2020 conference call participants, the question remains as to what to do with the road that is blocking flow between the coastal wetland and Lake Superior. This has led to more questions about impacts for larger cruise ships and their increases and changes of wave actions at the shoreline. Changes in wave frequency and intensity along the shoreline has the potential to change coastal features and processes. A similar setting at Boston Harbor Islands National Recreation Area resulted in a study about boat-wake impacts on coastlines (see Fitzgerald et al. 2011 referenced in Thornberry-Ehrlich 2017). They combined climatological data, hydrodynamic measurements (wave climate, wakes, and currents), suspended sediment measurements, and rates/profiles of bluff retreat in areas sited along the major ferry routes, finding that boat wakes have the potential to enhance wave energy.
- Locating a source of soil-saturating water that is exacerbating erosion and slumping along Munising Falls trail and how to manage said trail issues. This resulted in an internal memorandum by Martin (2018).

Pictured Rocks National Lakeshore Documents

The National Park Service has finalized a foundation document for the lakeshore (National Park Service 2016), but not yet a natural resource condition assessment or a resource stewardship strategy, all of which will be primary sources of information for resource management within the lakeshore. The foundation document listed the following fundamental resources and values, which are resource management priorities: (1) geomorphic processes and associated features, (2) access to diverse recreational opportunities, (3) visual resources, (4) wilderness, (5) ecosystem integrity, (6) abundance and quality of water resources, (7) maritime heritage resources, and (8) collaborative conservation. The first and sixth of these are significant with respect to the GRI (see "Geologic Setting and Significance" section).

The foundation document noted the following data needs: landscape change photography, documentation of the human footprint in the wilderness, inventory and assessment of dune blowouts, and inventory of infrastructure left stranded in wilderness areas.

Cultural landscape restoration, administration, and management are addressed in publications including Karamanski (1995), Labadie (1989), and Torres (1978). However, gathering of cultural landscape data as part of an inventory remains a research need at the lakeshore (National Park Service 2016).

Geologic Information Specific to the Pictured Rocks National Lakeshore Area

- Farrand and Drexler (1985) and Blewett (1994) detailed the deglaciation history of the Lake Superior basin.
- Karrow et al. (2000) detail the three parts of the Wisconsinan glacial stage, also referred to as "episode," which are further subdivided as follows: the Ontario subepisode (formerly Early Wisconsinan) comprises the Greenwood, Willowvale, and Guildwood phases; the Elgin subepisode (formerly Middle Wisconsinan) comprises the Port Talbot, Brimley, and Farmdale phases; and the Michigan subepisode (formerly Late Wisconsinan) consists of Nissouri, Erie, Port Bruce, Mackinaw, Port Huron, Two Creeks, Onaway, Gribben, Marquette, Abitibi, and Driftwood phases. Interglacial time to the present is the Hudson glacial stage or episode.
- Hart and Gafvert (2006) outlined a data management strategy to provide scientifically and statistically sound data to support management decisions for the protection of park resources for the Great Lakes Network including Pictured Rocks National Lakeshore.
- Blewett (2012) focused on the lakeshore's geologic story including a regional setting, bedrock record, ancient lakes and old shorelines, ice age glaciations, and more recent history. A road log provides field trip potential.
- Schaetzl et al. (2013) focused on Michigan physiography.
- Fisher and Hansen (2014) detailed coastline and dune evolution along the Great Lakes.
- The Michigan Geological Survey provides publications and data on its website (https://wmich.edu/geologysurvey). The website also provides geologic news, maps, natural resources production charts, and geothermal data, as well as subsurface cores, samples, and well records.

NPS Resource Management Guidance and Documents

- NPS *Management Policies 2006* (Chapter 4: Natural Resource Management): https://npspolicy.nps.gov/
- 1998 National Parks Omnibus Management Act: https://www.congress.gov/bill/105th-congress/senate-bill/1693
- Natural Resource Inventory and Monitoring Guideline (NPS 75): https://irma.nps.gov/DataStore/Reference/Profile/622933
- Natural Resource Management Reference Manual #77 (NPS 77): https://irma.nps.gov/DataStore/Reference/Profile/572379
- Resist-Accept-Direct (RAD)—A Framework for the 21st-Century Natural Resource Manager: https://doi.org/10.36967/nrr-2283597

Geologic Resource Laws, Regulations, and Policies

Table 4 was developed by the NPS Geologic Resources Division. It summarizes laws, regulations, and policies that specifically apply to NPS minerals and geologic resources. The table does not include laws of general application (e.g., 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.

Table 4. Geologic resource laws, regulations, and policies.

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

Table 4, continued. Geologic resource laws, regulations, and policies.

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

Table 4, continued. Geologic resource laws, regulations, and policies.

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

Table 4, continued. Geologic resource laws, regulations, and policies.

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

Table 4, continued. Geologic resource laws, regulations, and policies.

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

Table 4, continued. Geologic resource laws, regulations, and policies.

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

Table 4, continued. Geologic resource laws, regulations, and policies.

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

Table 4, continued. Geologic resource laws, regulations, and policies.

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

Table 4, continued. Geologic resource laws, regulations, and policies.

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

Additional References, Resources, and Websites

Michigan Geology

- Michigan Geological Survey: https://wmich.edu/geologysurvey

Climate Change Resources

- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/
- NPS Climate Change Response Program resources: http://www.nps.gov/subjects/climatechange/resources.htm
- NPS Sea Level Rise Map Viewer: https://maps.nps.gov/slr/
- NPS Climate Change, Sea Level Change: https://www.nps.gov/subjects/climatechange/sealevelchange.htm/index.htm
- US Global Change Research Program: http://www.globalchange.gov/home
- Earthquakes
- ShakeAlert: An Earthquake Early Warning System for the West Coast of the United States (sponsored by the US Geological Survey [USGS]): https://www.shakealert.org/
- USGS Earthquake Hazards Program, Unified Hazard Tool: https://earthquake.usgs.gov/hazards/interactive/

Geologic Maps

- Meeting Challenges with Geologic Maps (sponsored by American Geosciences Institute):: https://www.americangeosciences.org/environment/publications/mapping

Geological Surveys and Societies

- Michigan Geological Survey: https://wmich.edu/geologysurvey
- 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/

Geology of National Park Service Areas

- NPS Geologic Resources Division: https://www.nps.gov/orgs/1088/index.htm
- NPS Geodiversity Atlas: https://www.nps.gov/articles/geodiversity-atlas-map.htm
- NPS Geologic Resources Inventory: http://go.nps.gov/gri
- NPS Geoscience Concepts: https://www.nps.gov/subjects/geology/geology-concepts.htm

Landslide Information

- *"Monitoring Slope Movements"* (Wieczorek and Snyder 2009) in Geological Monitoring (Young and Norby 2009): https://www.nps.gov/articles/monitoring-slope-movements.htm
- *The Landslide Handbook—A Guide to Understanding Landslides* (Highland and Bobrowsky 2008): http://pubs.usgs.gov/circ/1325/

NPS Reference Tools

- NPS Technical Information Center (TIC) (repository for technical documents): https://www.nps.gov/dsc/technicalinfocenter.htm
- GEOREF, the premier online geologic citation database. The GRI team collaborates with TIC to maintain an NPS subscription to GEOREF via the Denver Service Center Library interagency agreement with the Library of Congress. Multiple portals are available for NPS staff to access these records.
- NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/). GRI staff uploads scoping summaries, maps, and reports to IRMA.
- GRI Publications:https://www.nps.gov/subjects/geology/geologic-resources-inventory-products.htm

US Geological Survey Reference Tools

- National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/ngmdb/ngmdb_home.html
- Geologic Names Lexicon (GEOLEX): http://ngmdb.usgs.gov/Geolex/search
- Geographic Names Information System (GNIS): https://www.usgs.gov/faqs/what-geographic-names-information-system-gnis
- USGS Store, Map Locator: http://store.usgs.gov
- USGS Publications Warehouse: http://pubs.er.usgs.gov
- A Tapestry of Time and Terrain: http://pubs.usgs.gov/imap/i2720/

Geologic Map Data

A geologic map in GIS format is the principal deliverable of the GRI program. GRI GIS data produced for the lakeshore follows the source maps listed here and includes components described in this chapter. 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, https://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 (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. The GRI team produced bedrock and surficial maps for the lakeshore, which are available for download at https://irma.nps.gov/DataStore/Reference/Profile/2175788.

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 include 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 ancillary map information document (piro_geology.pdf). The GRI team used the following sources to produce the GRI GIS data sets for the lakeshore. These sources also provided information for this report. When applicable, this report references them collectively as "GRI GIS source data."

Bedrock source maps:

- Reed and Daniels (1987) used for geologic map points, lines, and polygons
- Hamblin (1958) used for ages and unit descriptions
- Hussey (1952) used for ages and unit descriptions
- Milstein (1987) used for ages and unit descriptions

The GRI GIS bedrock data include the Trempealeau Formation (**Ct**) above the Munising Formation (**Cm**); however, review of fossil evidence and research of other sources preclude the presence of a Trempealeau Formation in the Pictured Rocks National Lakeshore area (Justin Tweet, National Park Service, paleontologist, written communication, 28 July 2020). The GRI map team is investigating the possibility of updating bedrock mapping with a more accurate and detailed source scale and to correct these geologic map unit discrepancies. This report reflects the existing GRI GIS data while identifying the need for more accurate source map information.

Surficial source map:

- Supplemental map in VanderMeer et al. (2020)

VanderMeer completed original surficial mapping in 2017 for a PhD dissertation. The publication VanderMeer et al. (2020) detailed the surficial mapping process and findings and provided a geologic map poster as supplemental material.

GRI GIS Data

The GRI team standardizes map deliverables by using a data model. This section references the GRI GIS data sets that were compiled in 2022. The GRI GIS data may be updated if new, more accurate geologic maps become available or if software advances require an update to the digital format. The GRI GIS data for the lakeshore were compiled using data model version 2.3, which is available at http://go.nps.gov/gridatamodel. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI Geologic Maps website, http://go.nps.gov/geomaps, provides more information about the program's map products.

The GRI team produced two datasets for the lakeshore, a bedrock geology data set and a surficial geology data set. These 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 sets:

- GIS readme file (piro_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;
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- Ancillary map information document (piro_geology.pdf) that contain information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures; and
- ESRI map documents (piro_bedrock_geology.mxd and piro_surficial_geology.mxd) that display the GRI GIS 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 the GRI team with any questions.

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features. Based on the source map scales—1:500,000 for the bedrock map and 1:24,000 for the surficial map—and US National Map Accuracy Standards, geologic features represented in the geologic map data are expected to be horizontally within 254 m (834 ft) and 12 m (40 ft), respectively of their true locations.

Additional GIS Data Sources

- NPS boundary GIS layer (2022): https://irma.nps.gov/DataStore/Reference/Profile/2225713
- Pictured Rocks National Lakeshore tract and boundary data: https://irma.nps.gov/Datastore/Reference/Profile/1048185
- NPS Soil Resources Inventory product: https://irma.nps.gov/Datastore/Reference/Profile/1048957
- NPS Vegetation Mapping Inventory geospatial data: https://irma.nps.gov/Datastore/Reference/Profile/2233355
- Great Lakes Network, landscape disturbance data: https://irma.nps.gov/Datastore/Reference/Profile/2217357
- Pictured Rocks National Lakeshore, landcover data: https://irma.nps.gov/Datastore/Reference/Profile/2166993
- Great Lakes Shoreviewer: https://irma.nps.gov/Datastore/Reference/Profile/2192436
- Shoreline length and water area in Great Lakes parks: https://irma.nps.gov/Datastore/Reference/Profile/2180595

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