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Natural Resource Stewardship and Science

Apostle Islands National Lakeshore

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2015/972

ON THIS PAGE
An opening in an ice-fringed sea cave reveals ice flows on Lake Superior.
Photograph by Neil Howk (National Park Service) taken in winter 2008.

ON THE COVER
Wind and associated wave activity created a window in Devils Island Sandstone at Devils Island.
Photograph by Trista L. Thornberry-Ehrlich (Colorado State University) taken in summer 2010.

Apostle Islands National Lakeshore

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

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Executive Summary

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI. This report synthesizes discussions from a scoping meeting for Apostle Islands National Lakeshore (Wisconsin) on 20–21 July 2010 and a follow-up conference call on 19 June 2014, which were held by the NPS Geologic Resources Division to determine geologic resources, the status of geologic mapping, and geologic resource management issues and needs. It is a companion document to previously completed GRI digital geologic map data.

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

Established on 26 September 1970, Apostle Islands National Lakeshore (Wisconsin) preserves and protects the natural and cultural resources on 21 of the 22 islands in southwestern Lake Superior off the coast of the Bayfield Peninsula. The names of the islands are Basswood, Bear, Cat, Devils, Eagle, Gull, Hermit, Ironwood, Long, Manitou, Michigan, North Twin, South Twin, Oak, Otter, Outer, Raspberry, Rocky, Sand, Stockton, and York. The "22nd island," Madeline Island, is privately owned. The lakeshore also includes 19 km (12 mi) of mainland shoreline along the northwestern edge of the peninsula.

Among the myriad features of the Apostle Islands' shorelines are sea cliffs and bluffs, sea caves, sandscapes, terraces, wave-cut benches, and arches. Sandscapes include sand spits, cuspate forelands, beaches, tombolos, barrier spits, and dunes. Inland features include glaciated landscapes where glaciers scoured bedrock, forming grooves and striations, while depositing thick mantles of glacial sediments elsewhere. The glacial-till bluffs are the most prolific source of sediment for the sandscapes within the lakeshore.

The geologic units within the lakeshore reveal a long geologic history stretching back more than a billion years. Sandstone of the 1.1-billion-year-old Bayfield Group—Orienta, Devils Island, and Chequamegon sandstone (geologic map units **PCo**, **PCdi**, and **PCch**, respectively)—collected in a series of braided streams and shallow lakes within a valley that was the setting of a continental rift in the midst of the ancient North American continent (or "craton"). Volcanic rocks associated with the rift, analogous to the modern East African Rift, are buried beneath the sandstones of the Bayfield Group. These sandstones and volcanic rocks were deeply buried, but are now exposed at the surface following hundreds of millions of years of erosion and weathering. During the ice ages (Pleistocene Epoch), more than a billion years later, glaciers scoured the bedrock, following stream valleys between resistant rock knobs that would become the Apostle Islands. The glaciers left a series of glacial deposits across the local landscape. These deposits consists of the Miller Creek and Copper Falls formations (**Qw**, **Qb**, **Qgh**, **Qgl**, **Qgw**, **Qou**, **Qsc**, **Qsg**, **Qsu**, **Qsuc**, and **Qgg**). In a dramatic example of an unconformity (gap in the geologic record), the ancient sandstones are juxtaposed against the youngest unit in the lakeshore—postglacial deposits, shoreline sediment (**Qc**). This unconformity represents 1,100,000,000 years of "missing time."

Geologic features and processes include the following:

- Apostle Islands. Every island has its own landscape characteristics reflected in geologic features, habitats, histories, and modern stories. All except Long Island are underlain by sandstone bedrock.
- Lake Superior Shoreline. Shorelines within the lakeshore are extremely dynamic. Approximately 257 km (160 mi) of shoreline exist within the lakeshore boundaries and comprise a wide variety of wave energies, ranging from exposed, high-

energy locations to sheltered, low-energy sites.

- Sea Caves and Other Shoreline Erosional Features. Waves sculpt bedrock shores into sea caves, arches, stacks, and cliffs. Glacial-till bluffs form where waves reach portions of the islands underlain by thick glacial deposits.
- Sandscapes. In areas of lower energy, sand collects in a series of forms called sandscapes. These include cuspate forelands, tombolos, beaches, and barrier spits.
- Fluvial Features. The primary fluvial feature within the lakeshore is the Sand River on the Bayfield Peninsula. On the islands, springs and seeps and ephemeral streams occur. Larger rivers throughout the region are important contributors of sediment to the regional lakeshore system, including to the local formation of the Long Island barrier spit.
- Recent Surficial Deposits. Unconsolidated surficial deposits are constantly being deposited and reworked on the landscape. These deposits include stream sediment (**Qsm**), shoreline sediment (**Qc**), and organic sediment (**Qp**) such as peat collecting in quiet water lagoons and bogs.
- 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 flowing between resistant knobs of bedrock defined the shapes of the Apostle Islands. Drumlins, ridges, 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 such as clay-rich glacial till, and (2) those deposited by meltwater in rivers (glaciofluvial) or lakes (glaciolacustrine).
- Slope Movements. Slope movements (the downslope transfer of earth materials) occur as small-scale landslides, slumps, and slope creep on the steep glacial-till bluffs. The bedrock cliff areas are prone to blockfall, topple, and small-scale slides.
- Sedimentary Rock Features. The rocks that form the foundation of Apostle Islands National Lakeshore contain many features indicative of their geologic history. The billion-year-old sedimentary rocks of the Midcontinent rift in Wisconsin are among the oldest in the Midwest. They collected in braided streams and shallow ponds of a rift valley.
- Devils Island Sandstone Type Locality. The excellent exposures of ancient sandstone at Devils Island have made it the type locality for the Devils Island Sandstone (**PCdi**). A type locality showcases a particular unit's mappable features, including rock type, color, texture, thickness, and distinguishing features such as depositional structures and the characteristic manner in which it weathers or erodes.
- Douglas Fault and Other Faults. Faults are fractures in rock along which rocks have moved. The Douglas Fault cuts across the base of the Bayfield Peninsula, south of Apostle Islands National Lakeshore. This fault is a reverse fault, thrusting older volcanic rocks over younger sedimentary rocks. It was likely a reactivated structure (i.e., normal fault) that first formed in association with the Midcontinent rift.
- Aeolian Processes. Windblown erosion, transportation, and deposition of sediments have led to the formation of dunes, barriers, and sand spits at Apostle Islands National Lakeshore. Sand is blasted from the exposed faces of glacial-till bluffs by the local winds, serving as a vital source of sediment.
- Paleontological Resources. Fossils are evidence of life preserved in a geologic context. The ancient bedrock of the lakeshore is unlikely to bear body fossils, but potential trace fossils, such as burrows, are in the Devils Island Sandstone (**PCdi**). The discovery of Pleistocene and Holocene fossils has potential at the lakeshore. These remains of past life could wash onto the shorelines or occur within peat (**Qp**).

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

- Shoreline Response to Lake-Level Change. The shorelines at the lakeshore are vulnerable to negative impacts from lake-level changes. Lake levels are controlled by factors including climate, local uplift or subsidence, and land use. The northeastern Lake Superior basin is uplifting faster than the Apostle Islands area, which could cause lake-level rise, flooding shorelines and inundating infrastructure. Contrary to a marine coastal setting where relative sea level is predicted to rise, climatic models predict lake levels will drop, exposing docks, sand bars, and submerged resources throughout the area. Lake levels are intimately tied to climate changes. 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.

- Slope Movement Hazards and Risks. 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, involves the construction of stabilizing structures to protect cultural resources and visitor access.
- Caves and Associated Landscape Management. The shallow sea caves at the lakeshore are non-renewable resources formed in the sandstone cliffs at the shorelines. These features tend to weather relatively quickly and change rapidly. The lakeshore does not have a cave management plan, but climbing within the caves is restricted.
- Fluvial and Other Surface Water Issues. As the Sand River meanders across its floodplain, it erodes into the unconsolidated deposits flanking its channel and causes undercutting and slope movements. Several open-water lagoons associated with sandscapes on the Apostle Islands are naturally acidic and lack the ability to buffer acid deposition from precipitation.
- Abandoned Mineral Lands. Four abandoned mineral lands features occur at four sites on three islands at Apostle Islands National Lakeshore: Breckenridge Quarry and Bass Island Brownstone, Ashland Brownstone Company, and Excelsior Brownstone Quarry.
- Disturbed Land Restoration. Apostle Islands National Lakeshore includes a long history of human use. Most disturbed features are being allowed to reach a natural state of equilibrium. Some are interpreted for visitors.
- Renewable Energy Development. Generation and transmission of renewable energy includes utility-scale onshore and offshore wind, solar, geothermal, and hydroelectricity. Proposals exist to develop wind farms on Madeline Island and the mainland with potential impacts to the lakeshore's viewshed and local traffic.
- External Mineral Development. A large iron mine is proposed for an area in the Gogebic Iron Range, 50 km (30 mi) southeast of Apostle Islands National Lakeshore. Potential negative impacts to the lakeshore from mining include water quality degradation, air pollution, increased traffic, and noise.
- Wind-Speed Change. Local wind speeds are increasing at rates approaching 5% per decade. The increase is probably driven by global climate change. Increased wind speeds will accelerate erosion of glacial-till bluffs, increase tree blowdowns, and change the formation of aeolian features in the sandscapes.
- Seismic Activity Hazards and Risks. Earthquakes that are noticeable by humans are uncommon in Wisconsin. Buried faults and other structures could become active due to the isostatic rebound of the land surface as Earth's crust continues to adjust to the retreat of glacial ice after the ice ages.
- Paleontological Resource Inventory, Monitoring, and Protection. The lakeshore lacks a field-based paleontological resource survey. Such a survey could provide detailed, site-specific descriptions and resource management recommendations for all paleontological resources at the lakeshore.

Products and Acknowledgments

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

GRI Products

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

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

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

Additional information regarding the GRI, including contact information, is available at http://www.nature.nps.gov/geology/inventory/ (accessed 3 April 2015). The current status and projected completion dates of products are available at http://www.nature.nps.gov/geology/GRI_DB/Scoping/Quick_Status.aspx (accessed 3 April 2015).

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Geologic Setting and Significance

This section describes the regional geologic setting of Apostle Islands National Lakeshore and summarizes connections among geologic resources, other park resources, and park stories.

Park Setting

Apostle Islands National Lakeshore, established on 26 September 1970, preserves and protects the natural and cultural resources on 21 of the 22 islands in southwestern Lake Superior off the coast of the Bayfield Peninsula in northern Wisconsin (fig. 1, in pocket). Jordahl (1994) detailed the story behind the establishment of the lakeshore. The islands' name may stem from early French explorers, who referred to them collectively after the 12 biblical apostles, or perhaps the name is inspired by a band of "renegades" who used the narrow winding straits, caves, and hidden coves during their hijacking of the payloads of local fur traders (Stucker 1974). The 21 islands within the national lakeshore are Basswood, Bear, Cat, Devils, Eagle, Gull, Hermit, Ironwood, Long (currently a sand spit), Manitou, Michigan, North Twin, South Twin, Oak, Otter, Outer, Raspberry, Rocky, Sand, Stockton, and York. The largest Apostle Island, Madeline Island, is privately owned. The total area contained within the lakeshore's boundaries is 28,074 ha (69,372 ac) of which 13,557 ha (33,500 ac) are designated wilderness and 11,020 ha (27,232 ac) are submerged; the lakeshore boundary extends 0.40 km (0.25 mi) offshore on the lake surface. The lakeshore also includes 19 km (12 mi) of mainland shoreline along the northwestern edge of the Bayfield Peninsula. The mainland unit, and Eagle Sand, York, and Raspberry islands are within Bayfield County; the remaining islands are in Ashland County.

The shoreline of Lake Superior is 183 m (602 ft) above sea level. The highest point of the Bayfield Peninsula is 251 m (824 ft) above the lake's surface. Most of the islands rise less than 60 m (200 ft) above the lake's level. The highest island, Oak Island, is 329 m (1,081 ft) above sea level. Oak Island covers approximately 2,000 ha (5,000 ac) and has about 146 m (479 ft) of relief. The shorelines of the Apostle Islands display sea cliffs and bluffs, sea caves, sandscapes, terraces, wave-cut benches, and arches. Sandscapes include sand spits, cuspate forelands, beaches, tombolos, barrier spits, and dunes. Inland features include glaciated landscapes where glaciers simultaneously scoured some areas and deposited thick mantles of glacial deposits in others.

Geologic Setting

Wisconsin consists of five physiographic provinces: Lake Superior Lowland, Northern Highland, Central Plain, Western Upland, and Eastern Ridges and Lowlands (fig. 2; Martin 1916; Dott and Attig 2004). Physiography is determined largely by the variations of texture, composition, and structure of the underlying rocks and how earth surface processes have shaped their characteristic topography. Apostle Islands National Lakeshore is entirely within the northernmost province, the Lake Superior Lowland. The steeply rising shores of Lake Superior are testament to its setting as a lake set deeply within a highland area. The southern boundary of the province is the highest abandoned beach line of Lake Superior (Martin 1916).

The geologic setting of Lake Superior and the Apostle Islands is reflective of its long geologic history. The geologic units within the lakeshore are from opposite ends of the geologic time scale (fig. 3): the billion-year-old bedrock from the Mesoproterozoic Era (or younger, possibly Neoproterozoic Era, as accurate age dates do not exist [Richard Ojakangas, University of Minnesota Duluth, geologist, written communication, 12 January 2015]), and recent Pleistocene and Holocene surficial units, some of which are still forming. The bedrock exposed in the lakeshore (geologic map units **PCch**, **PCdi**, and **PCo**) is the youngest part of the Keweenawan Supergroup—rocks that formed as part of the Midcontinent rift approximately 1.1 billion years ago. The Middle Proterozoic Midcontinent rift system is one of Earth's great continental rifts (Hinze et al. 1997). The rift extends more than 2,500 km (1,500 mi) from Kansas in a northeasterly arc through the Lake Superior region and down into southern Michigan (fig. 4). More than 30 km (18 mi) of volcanic and sedimentary rocks fill the rift, but they are only exposed in the Lake Superior region as a result of long-term erosion and cover by younger Paleozoic rocks. Along the southern shore of Lake Superior, rocks of the Keweenawan Supergroup have been tilted to the north, forming the Montreal River monocline (Cannon et al. 1999). Locally, the Keweenawan Supergroup is draped over an Archean (more than 2.5 billion years old) block

Figure 2. Physiographic provinces of Wisconsin. Apostle Islands National Lakeshore (green box) is within the Lake Superior Lowland province, which contains some of the oldest geologic units in the state. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using information from Martin (1916) and the Wisconsin Geological and Natural History Survey. Shaded-relief base map by Tom Patterson (National Park Service), available at http://www.shadedrelief.com/physical/index.html (accessed 16 June 2014).

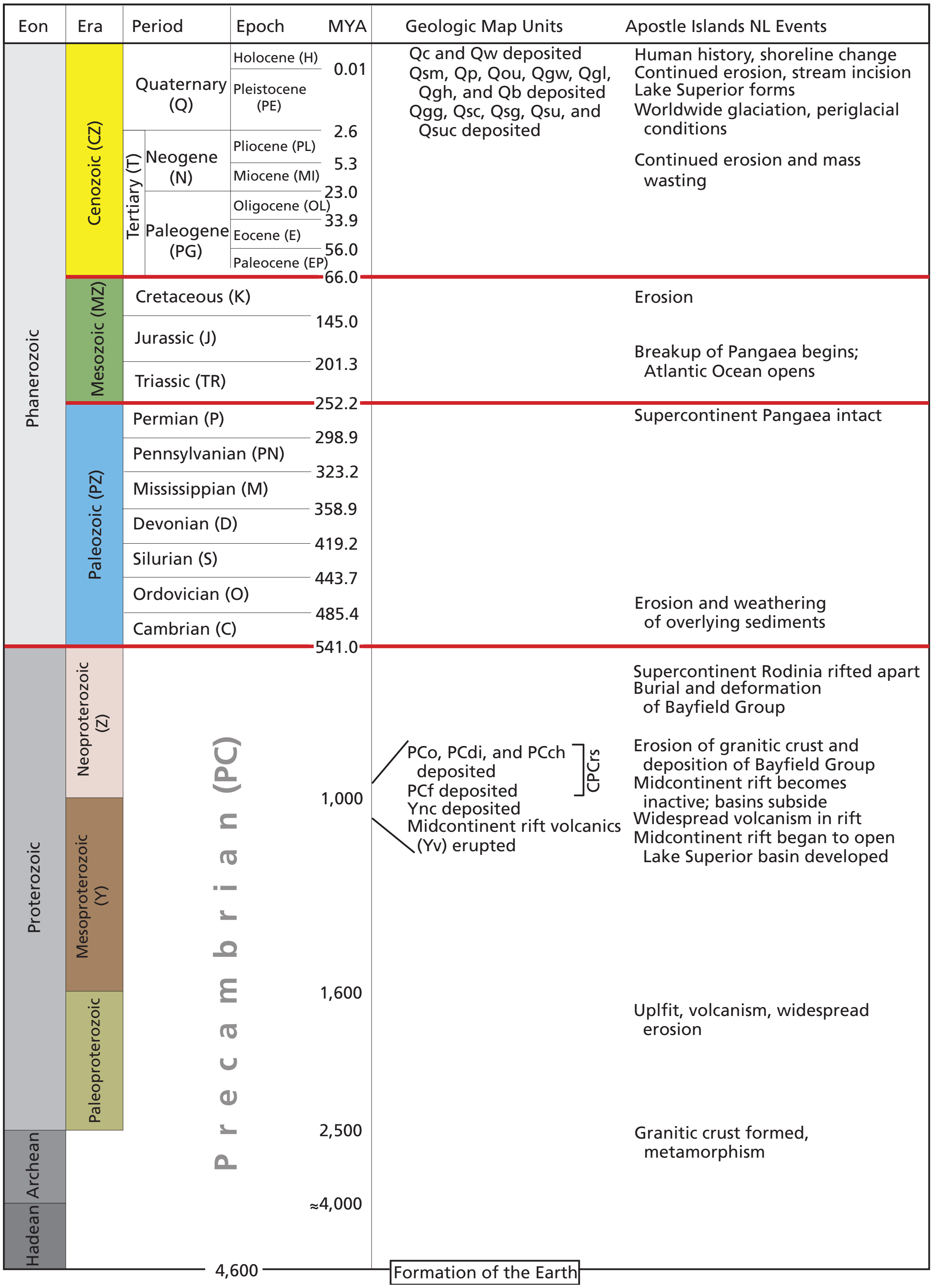


Figure 3. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. Boundary ages are millions of years ago (MYA). National Park Service graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 5 April 2015).

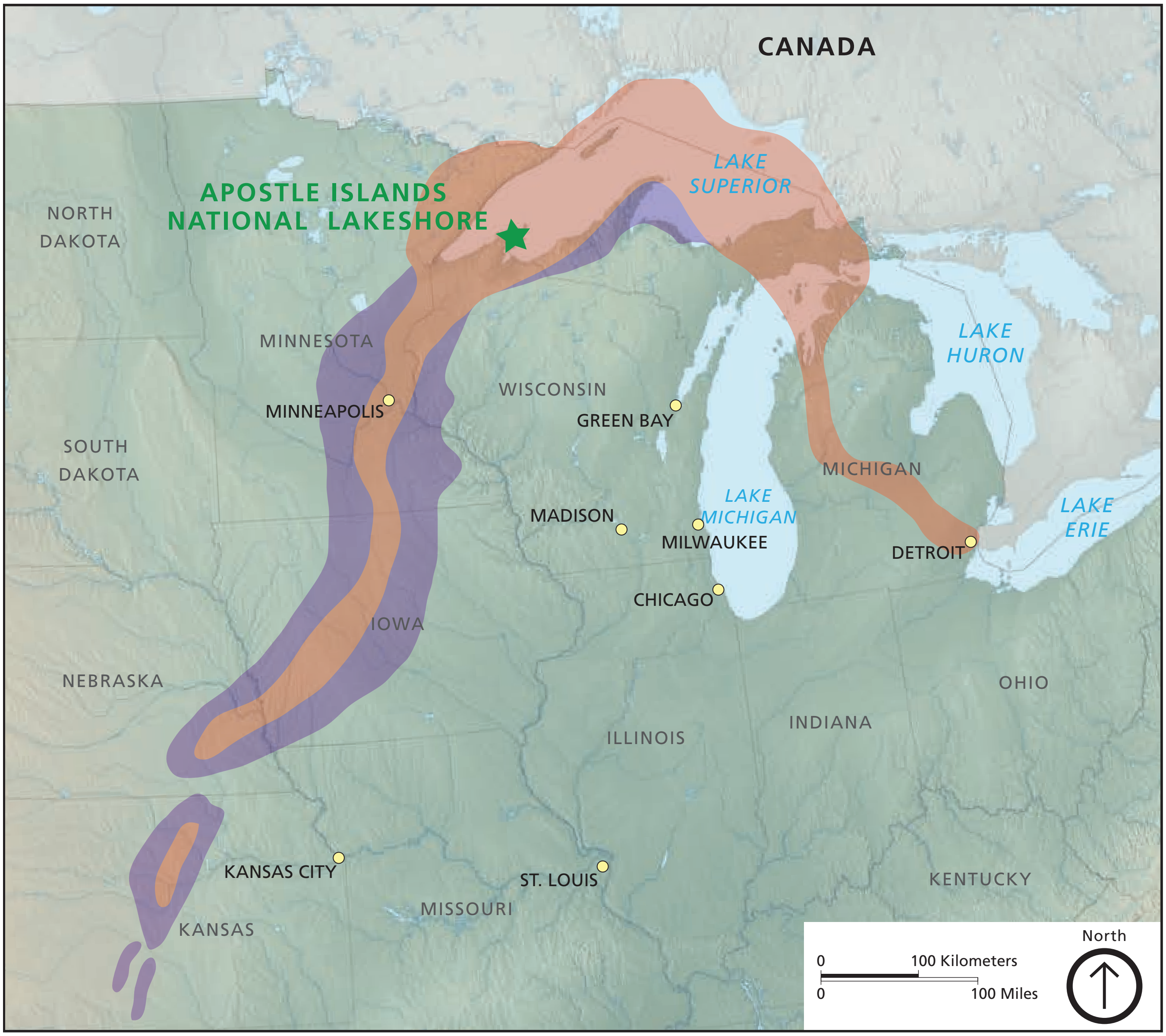


Figure 4. Map of the Midcontinent rift. Orange areas delineate the primary volcanic basins with associated sedimentary and plutonic rocks. The purple areas represent primarily sedimentary rocks deposited after volcanism had ceased. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after 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 18 August 2014).

called White's Ridge (fig. 5). At Apostle Islands National Lakeshore the sandstones of the Bayfield Group, made up of the Orienta Sandstone (**PCo**), Devils Island Sandstone (**PCdi**), and Chequamegon Sandstone (**PCch**), accumulated after volcanism associated with active rifting had ceased. The rift was buried for hundreds of millions of years until glaciers—an agent of profound landscape change—scoured and sculpted the Lake Superior basin in the ice ages of the Pleistocene Epoch (2.6 million–11,700 years ago; fig. 3).

Huge glaciers intermittently advanced and retreated through the Superior region. They scoured vast channels in the bedrock leaving "islands" between them. The glaciers and associated meltwater deposited vast amount of glacial drift or mixed glacial sediments across the region, including the Miller Creek Formation (**Qw**, **Qb**, **Qgh**, **Qgl**, **Qgw**, and **Qou**) and Copper Falls Formation (**Qsc**, **Qsg**, **Qsu**, **Qsuc**, and **Qgg**) (fig. 6; Clayton 1984, 1985). When they retreated, a series of glacial lakes, including Glacial Lake Duluth, formed

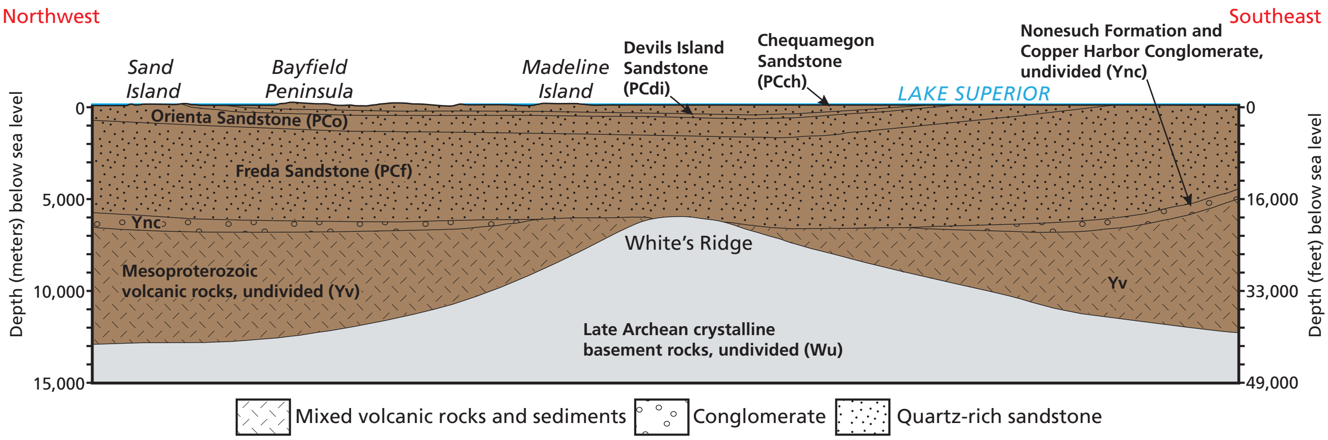


Figure 5. Cross section through Apostle Islands and the Bayfield Peninsula. Note the buried structure of White's Ridge. Cross section follows the northwestern part of the A–A´ cross section line included in the GRI GIS data. Colors are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps; they also correspond to the colors on the Map Unit Properties Table. See the Map Unit Properties Table (in pocket) for more detail. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Cannon et al. (1996, cross section A–A´).

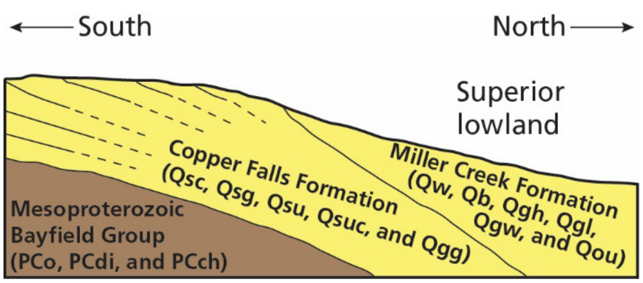


Figure 6. Cross section through Pleistocene and Holocene deposits in the Apostle Islands area. Cross section is from south to north showing relationships between the two major Pleistocene into Holocene units (Copper Falls and Miller Creek formations). These units unconformably overlie rocks of the much older Precambrian Bayfield Group. Colors are standard US Geological Survey colors to indicate different time periods on geologic maps; they also correspond to the colors on the Map Unit Properties Table (in pocket). Graphic is not to scale and is vertically exaggerated. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Clayton (1984, figure 3).

in the Superior basin. Remnants of these glacial-lake shorelines, in places 150 m (500 ft) above the modern shoreline, occur at Apostle Islands National Lakeshore (National Park Service 2005). Lake Superior and the other Great Lakes assumed their present configuration about 2,000 years ago when the lakes began to drain into the Atlantic Ocean via the St. Lawrence River (LaBerge 1994; Busch 2008).

Geologic Significance and Connections

The natural beauty of Apostle Islands National Lakeshore belies a long history of human use. As described in detail in Jordahl (1994) and Busch (2008), the human history of the Apostle Islands incorporates American Indians, voyageurs (canoemen), fur traders, fishing and logging developers, and farmers. The geologic resources and features of the islands fundamentally influenced this history.

American Indians took advantage of the natural richness of the landscape and established hunting and fishing camps, and harvested berries (Julie Van Stappen, written communication, 9 January 2015). Fluctuating lake levels may have obscured some of the earliest sites. A Paleo-Indian stone projectile from Manitou Island may indicate human presence as early as 11,000 years before present—a similar age to an archeological site on Chequamegon Bay (Busch 2008). Following the retreat of the glaciers, as vegetation became established, the woodland conditions allowed American Indians from the Archaic period (8,000 to 2,000 years before common era [BCE]) to find food, red clay for pottery, and stone tool material, including quartzite and native copper that was mined in the Lake Superior region, for example, at Isle Royale and the Keweenaw Peninsula (Jordahl 1994; Busch 2008). Copper was deposited in rift-related volcanic rocks by circulation of mineral-laden geothermal fluids. Projectiles, knapping debris, fire-cracked rock, and a worked copper blank were all found at sites on Stockton Island, some of which dated to 5,300 to 4,880 years before present (Busch 2008). The earliest evidence of the next archeological period, the Woodland, in the Apostle Islands also appears on Stockton Island as hearths, a midden, a range of stone tools, pottery, and animal remains. Chipped quartz cobbles are also known remnants from this time—about 1,200 years before present (Busch 2008), and were likely used as scrapers for fish processing (Julie Van Stappen, written communication, 9 January 2015).

American Indians speaking an Algonquian language, including the locally prominent Outchibouec or Ojibwe, were following the Late Woodland tradition when the first Europeans arrived in the early 17th century (Busch 2008). Chippewa legends describe the origin of the Apostle Islands as occurring when one of their ancestral figures and cultural heroes, Wanabozho, tried to trap a giant beaver behind a hastily built earth dam (Long Island) (Stucker 1974; Julie Van Stappen, written communication, 9 January 2015). The mythical beaver escaped, the dam failed, and the remnants of the dam are the Apostle Islands (Stucker 1974).

Local geologic features affected the area's early history. As described in the "Geologic History" section, drainage from glacial lakes following the last major ice age radically changed river courses. American Indians, early European explorers, and fur traders traversed a 4-km (2-mi) portage from the St. Croix River into the Brule River across the modern divide north of Solon Springs (Ojakangas et al. 2011). Fur traders entered the area in the early 1600s using the natural harbors and bays for trading points. By the end of that century a trading post, La Pointe, was established on Madeline Island to figure prominently for nearly 150 years (Stucker 1974). Once the fur trade declined, the logging industry took over, forever changing the forests and landscapes of the islands (Stucker 1974).

The Apostle Islands have a 30-year-history of brownstone (sandstone) quarrying. Beginning in 1869, Chequamegon Sandstone (**PCch**) was extracted from Stockton, Hermit, and Basswood islands for urban Midwest buildings. More than 42,000 m^3 (1.5 million ft^3) were removed by the Ashland Brownstone Company alone. The dark brown color of the sandstone comes from hematite (oxidized iron) that formed when the original sand deposits were exposed to oxygen in the atmosphere. Groundwater seeping through cracks in the sandstone left characteristic bleached fringes (Brown 2006); Thornberry-Ehrlich 2013). Lake Superior provided easy and economical boat transport of the quarried blocks (Brown 2006). The industry flourished until architectural styles changed, lighter colored stones (e.g., Indiana limestone) became fashionable, and extraction costs increased. Today, the dark, reddish brown stone is visible in the ca. 1883 Old Bayfield County Courthouse (now the Apostle Islands National Lakeshore visitor center) and other historic buildings throughout the Midwest (National Park Service 2005; Brown 2006). Apostle-Island quarries were abandoned by the late 1890s. Cut blocks are still visible on the shore of Hermit Island.

The bedrock-cored Apostle Islands, jutting off the Bayfield Peninsula, were perfect perches for lighthouses to guide ships to mainland harbors and away from rocky shoals and islands. The eight lighthouses and six light stations on Devils, Long, Michigan, Outer, Raspberry, and Sand islands form the largest single-park collection in the National Park System (Thornberry-Ehrlich 2013). The lighthouse towers were constructed between 1856 (Michigan Island) and 1929 (new Michigan light) (Julie Van Stappen, written communication, 9 January 2015).

Apostle Islands Ecosystem

The Apostle Islands and Lake Superior region experiences distinct seasonal changes and supports a variety of ecosystems. Because of its great size, Lake Superior creates a maritime climate in an otherwise northern, continental setting. Inherent in this maritime climate are relatively cool summers and warm winters compared to adjacent areas.

The glacial history and setting of the islands and Bayfield Peninsula strongly influenced the types of soils that developed and in turn the types of plants. Soils on glacial tills sourced from the Bayfield Group are very sandy and acidic, whereas soils developed on the Pleistocene lacustrine sediments tend to be very clay rich and somewhat calcareous (Cary et al. 1979). Soils began to develop on the Apostle Islands during the late Pleistocene–early Holocene (fig. 3: Cary et al. 1979). Soil resources are not covered in this geologic report, but an NPS Soil Resources Inventory product for Apostle Island National Lakeshore is available at https://irma.nps.gov/App/Reference/Profile/1049040 (accessed 3 April 2015).

Natural Resources Research Institute (2006) identified at least eight "important habitat sites" in the Apostle Islands National Lakeshore. Hardwood forests, dominated by maples and birches, are common throughout the Apostle Island region. Boreal forests of white spruce, balsam fir, tamarack, white cedar, birch, and aspen occupy a small portion of the islands' forests (Natural Resources Research Institute 2001; Busch 2008). A pine savannah forest, peat bog, beach grass dune, and freshwater lagoon thrive on the double tombolo connecting Stockton and Presque Isle islands. A number of rare plants, including carnivorous pitcher plants, grow there. Throughout human history, the Apostle Islands were heavily logged for white pine, hemlock, yellow birch, and maple; however, some virgin stands of hemlock, pine, and sugar-maple oak were not logged and remain among the natural treasures of the Apostle Islands (Swain and Winkler 1983; Busch 2008; Ojakangas et al. 2011). A stand of the original hemlock-hardwood forest exists on the northern end of Outer Island (Jordahl 1994). On islands where browsing deer have been restricted or absent, Canada yew is a dominant groundcover. Canada yew is all but gone on the adjacent mainland (Thornberry-Ehrlich 2013).

Beyond the forests, the islands' sandscapes, glacial-till bluffs, sandstone ledges and cliffs, and sphagnum bogs provide habitat for specialized plant communities (Busch 2008). These habitats support a variety of flora and fauna. More than 800 species of plants grow in the Apostle Islands, of which at least 37 are rare, endangered, or threatened (Jordahl 1994; National Park Service 2004). The geologic units of the lakeshore host 324 species of known lichen (Bennet and Wetmore 2005). Hundreds of species of nesting birds find habitat on the islands, including critical habitat for the endangered piping plover community that nests on Long Island (Thornberry-Ehrlich 2013). In addition, the islands provide an important stopover for migrating birds across the Great Lakes. More than 20 species of salamanders, toads, frogs, and reptiles (e.g., turtles and snakes) find suitable habitat on the islands (National Park Service 2004). Splash pools, developed on bedrock platforms located at the shore host myriad species including lichens; the arctic disjunct Birdseye Primrose (*Primula farinose*) at Devils Island; stone flies; predacious diving beetles; spring peeper and salamander; and invasive spiny water fleas (*Bythotrephes longimanus*) (Lafrançois et al. 2010). Apostle-Island shores are important fish spawning areas. At least 22 whitefish–important habitats and five lake trout–important habitats exist among the islands (Natural Resources Research Institute 2006). Mammal species such as black bears, beaver, deer, red squirrels, snowshoe hares, deer mouse, voles, foxes, coyotes, and otters occur on the islands (National Park Service 2004). The lakeshore's lighthouses, as well as the honeycombed sandstone cliffs, caves, and other shoreline exposures provide some bat habitat (Thornberry-Ehrlich 2013).

Geologic Features and Processes

This section describes noteworthy geologic features and processes in Apostle Islands National Lakeshore.

During the 2010 scoping meeting (Thornberry-Ehrlich 2013) and 2014 conference call, participants (Appendix A) identified the following geologic features and processes:

- Apostle Islands
- Lake Superior Shoreline
- Sea Caves and Other Shoreline Erosional Features
- Sandscapes
- Recent Surficial Deposits
- Fluvial Features
- Glacial Features
- Slope Movements
- Sedimentary Rock Features
- Devils Island Sandstone Type Locality
- Douglas Fault and Other Faults
- Aeolian Processes
- Paleontological Resources

Nuhfer and Dalles (2004) provide a comprehensive guidebook to the geology of each of the Apostle Islands at the lakeshore. The Apostle Islands serve as a natural classroom providing visitors the opportunity to learn about geological features and processes, including braided stream deposits, glacial scouring, shoreline erosion, sandscapes, sea caves, wave-cut platforms, and sedimentary structures (Nuhfer and Dalles 1994).

Apostle Islands

Each Apostle Island has its own unique character and landscape expressed through geologic features, habitats, histories, and modern uses as described in detail by Nuhfer and Dalles (2004). With the exception of Long Island—a barrier sand spit—the Apostle Islands are cored by sandstone bedrock extending outwards in a northeasterly trend from the tip of Bayfield Peninsula into Lake Superior (see poster, in pocket). Prior to the scouring of glaciers during the ice ages of the Pleistocene Epoch, the islands were part of the mainland. Their northeasterly trend parallels ancient streamflows, which deposited some of the sandstones of the Bayfield Group (geologic map units **PCo**, **PCdi**, and **PCch**), as well as more recently flowing glaciers (fig. 7; Cannon et al. 1999; Nuhfer and Dalles 2004).

The largest island in the lakeshore is Stockton Island at 4,069 ha (10,054 ac) and 36.5 km (22.7 mi) of shoreline. The smallest island is Gull Island at 1.2 ha (3 ac) and 0.6 km (0.4 mi) of shoreline. Most islands are two to three times longer than they are wide. Elevations above the Lake Superior shoreline range from 146 m (479 ft) at Oak Island to 3 m (10 ft) for Long and Gull islands. Visitors can access all of the islands by beach except Basswood, Devils, Eagle, Gull, and North Twin. With the exception of Gull Island, rock landings provide access to these islands.

The Apostle Islands experience constant landform change. When the Apostle Islands were surveyed by the General Land Office in 1856, Gull Island was 11 m (35 ft) above the lake level, vegetated, and inhabited (Jordahl 1994). By the 1920s after devastating storms, it was 0.6–1 m (2–3 ft) above the lake. Other islands such as Steamboat, which existed in 1898, have disappeared altogether (Stucker 1974; Ulf Gafvert, Great Lakes Network, GIS specialist; and Julie Van Stappen and Peggy Burkman, Apostle Islands National Lakeshore, chief of Resource Management and biologist, conference call, 19 June 2014).

Park resource managers are interested in how the shorelines and sandscapes (see “Sandscapes” section) have changed with time. In preparation of the book *A guidebook to the geology of Lake Superior’s Apostle Islands National Lakeshore* (Nuhfer and Dalles 2004), Ed Nuhfer took a number of photographs that extend back at least 20 years. This photographic record has management applications. Digitizing shorelines of the sand spits, repeat photography, and aerial photographs would all contribute to a quantitative understanding of shoreline change at Apostle Islands National Lakeshore. The Geoscientist-in-the-Parks program (http://www.nature.nps.gov/geology/gip/index.cfm; accessed 3 April 2015) may provide a means of facilitating such a project.

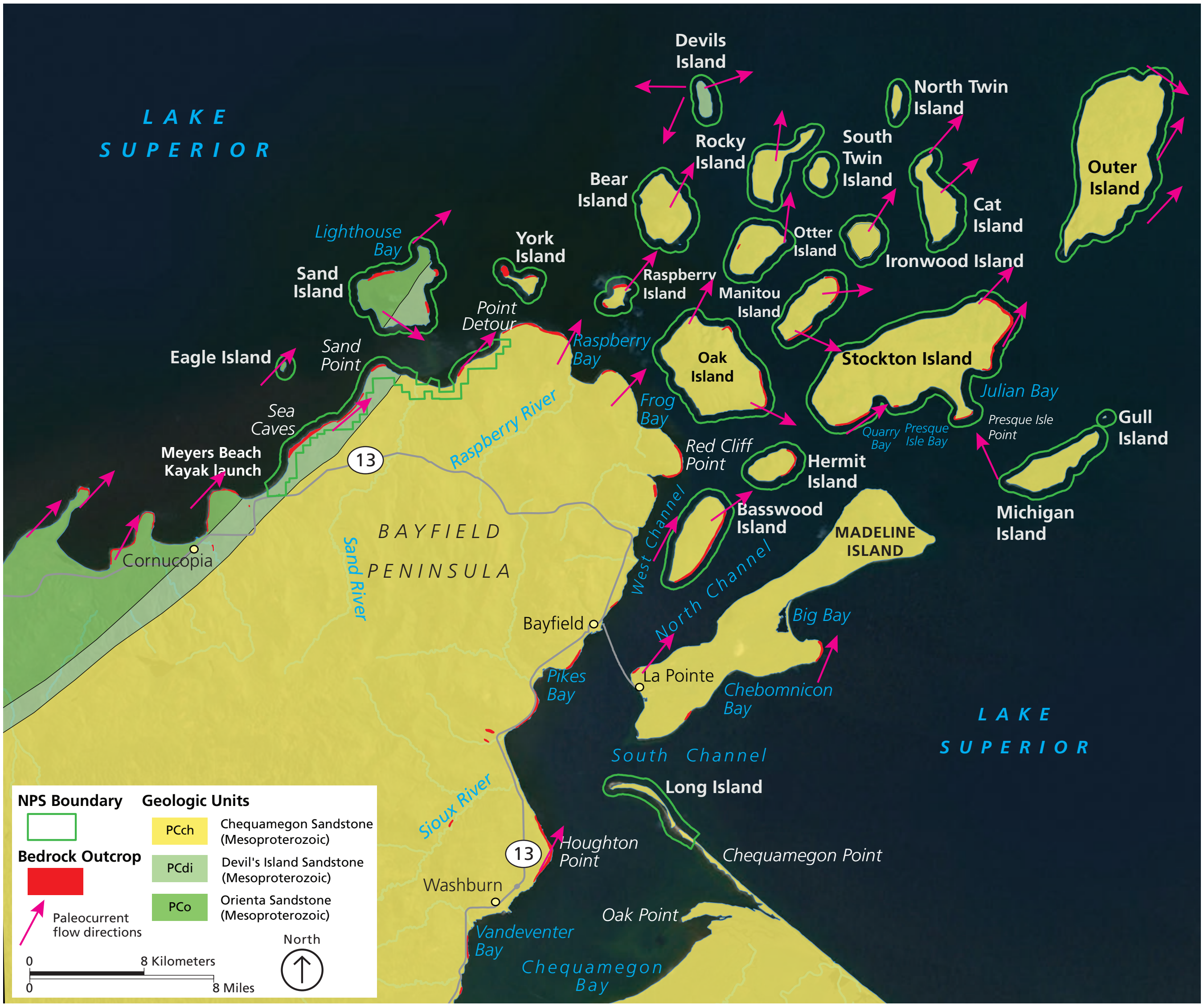


Figure 7. Apostle Islands and paleocurrent flow directions. Measurements on sedimentary structures such as cross-beds and ripple marks provide paleocurrent flow directions of rivers and shorelines that deposited the Mesoproterozoic bedrock of the Apostle Islands a billion years ago. Devils Island Sandstone (PCdi) has a wider range of flow-direction orientations due to its deposition in a shoreline environment compared to the stream currents that deposited the Orienta (PCo) and Chequamegon (PCch) sandstones. Because of the predominant stream flow directions to the northeast, bedrock exposures on the northwest or southeast sides of the islands will show layers deposited along the length of the ancient stream channels. Therefore, bedrock exposures on the northeast and southwest sides will typically show a "cross-section" of the ancient stream channels. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) and Georgia Hybels (Colorado State University) with data from Nuhfer and Dalles (2004, figure 5).

Lake Superior Shoreline

Coastal (shoreline) resources are in the transition between terrestrial (on land) and open-water environments. Coastal environments—shaped by waves, tides, and wind—include tidal flats, estuaries, dunes, beaches, and barrier islands (Bush and Young 2009). As of November 2011 (the most recent servicewide statistics), the National Park Service managed 84 ocean, coastal, and Great Lakes parks with more than 18,000 km (11,200 mi) of shoreline. The seven Great Lakes parks—Apostle Islands National Lakeshore, Grand Portage National Monument, Isle Royale National Park, Pictured Rocks National Lakeshore, Sleeping Bear Dunes National Lakeshore, Indiana Dunes National Lakeshore, and Perry's Victory and International Peace Memorial—have more than 998 km (620 mi) of shoreline (Curdts 2011). Approximately 257 km (160 mi) of shoreline exist within Apostle Islands National Lakeshore boundaries (Curdts 2011). The NPS Geologic Resources Division Coastal Geology website, http://nature.nps.gov/geology/coastal/index.cfm (accessed 3 April 2015), provides additional information.

The Apostle Islands are on the southwestern edge of Lake Superior, the largest freshwater lake (by surface area) in the world; it holds 10% of the liquid freshwater on Earth. Even at its great size of 82,170 km^2 (31,700 mi^2), Lake Superior is much smaller than an ocean and thus has smaller waves and currents (Engstrom 1985). Like all lakes, sediment is slowly accumulating in Lake Superior and streams incise the edges. For these reasons, lake waves and currents have insufficient time to create large landforms, such as would occur at an oceanic coast (Wycoff 1999).

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, have a period of 7.9 hours, and are almost always present in Lake Superior (Minnesota Sea Grant 2014). Seiches can cause "freak" or "rogue" 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 (Minnesota Sea Grant 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).

Within Apostle Islands National Lakeshore, a wide variety of wave energy settings exist, from exposed, high-energy locations to sheltered, low-energy locations (Engstrom 1974b). Waves wear away bedrock that fringes the lakeshore, undercutting the exposures (Wycoff 1999; National Park Service 2005). Bedrock outcrops tend to form cliff exposures on the north- and northeast-island shores in the face of the highest wave energy. Some of the larger bedrock exposures (e.g., **CPCrs** and "Outcrops" layer) are included in the GRI GIS data. Erosive waves sculpt the bedrock into myriad forms, including caves, arches, stacks, and cliffs. In shorelines underlain by glacial deposits, mostly on the western shores of the islands, waves have eroded steep till bluffs (see "Sea Caves and Other Shoreline Erosional Features" section). Waves and currents also transport sediments and deposit them in areas of lower energy. Sandscapes, including beaches with scarps, berms, and ridges, as well as sand spits, barrier spits and islands, tombolos, cuspate forelands, and dunes are formed and reworked by waves and wind (see "Sandscapes" section).

Shorelines within the lakeshore are dynamic areas capable of rapid change, which is commonly 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). Entire islands have disappeared or diminished dramatically (Julie Van Stappen and Peggy Burkman, conference call, 19 June 2014). Humans have witnessed entire sand beaches stripped away to bedrock by storms in a few hours. Then, the beaches were rebuilt as longshore currents moved sand back to the area over a period of a few weeks. Fallen trees and landslide scars mark areas of rapid erosion in the glacial-till bluffs—collectively, the single largest source of sediment to Lake Superior (Huff and Swenson 2002; Nuhfer and Dalles 2004). Along bedrock shores, arches collapse (e.g., Lookout Point off of Hermit Island in 1975); stacks and balancing rocks form and then crumble due to the relentless wave energy (e.g., at Stockton Island) (Nuhfer and Dalles 2004). New sea caves are rapidly developing at the southern end of Sand Island. The sea caves near Mawikwe Bay along the mainland unit shoreline are also changing rapidly (Nuhfer and Dalles 2004). See "Sea Caves and Other Shoreline Erosional Features" section and "Slope Movements" section).

Waves are not the only agent of shoreline change in Lake Superior. As water, seeps along cracks and fractures then freezes and expands, it wedges rock apart in a process called frost weathering. Furthermore, expanding lake ice pushes sand and gravel up the beach areas, creating ridges (Wycoff 1999; National Park Service 2005). Ice also pushes against low-lying shelves in the bedrock, and frozen spray icicles add tremendous weight to bedrock outcrops (Nuhfer and Dalles 2004).

Because of its large volume, Lake Superior seldom freezes over completely. The winter of 2013–2014 had

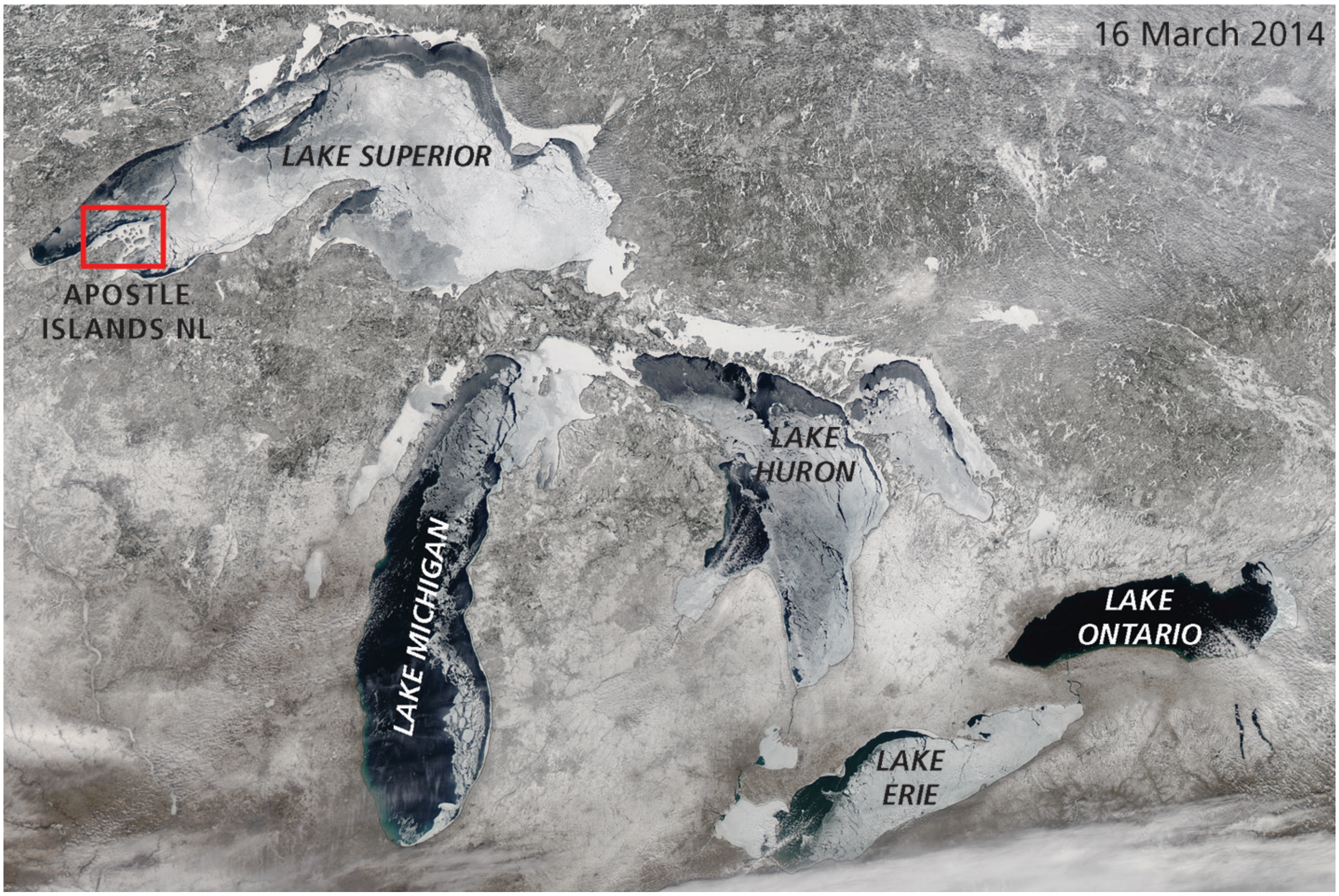


Figure 8. Frozen Lake Superior. This NASA satellite image of the Great Lakes was taken on 16 March 2014. Lake Superior was roughly 95% frozen on 19 March. Wave action pushed ice flows around the lakes' surface and had marked impacts on the shorelines at Apostle Islands National Lakeshore (red box). NASA image from the Moderate Resolution Imaging Spectroradiometer (MODIS) available at http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=85535 (accessed 7 May 2015).

prolonged cold spells and the lake was as much as 96% covered with ice (fig. 8; Rodman 2014). The lake was covered with a similar percentage of ice during the 2014–2015 winter. This ice cover prevented extensive winter-time evaporation and was responsible in part for higher than usual lake levels in spring 2014 after a trend and predictions of dropping levels (see "Shoreline Response to Lake-Level Change" section). The ice also formed ice caves and contributed to breaks and erosion of the sandstone cliffs. Ephemeral ice caves formed along the Lake Superior shorelines (fig. 9). The caves are formed by wind and wave action pushing slushy ice along the shoreline and large formations and columns are formed from seepage between the rock layers (Julie Van Stappen, written communication, 9 January 2015). The ice piles up in layers pocked with caves. The caves may feature ice stalactites.

Sea Caves and Other Shoreline Erosional Features

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). As of May 2015, cave or karst resources are documented in 153 parks, including Apostle Islands National Lakeshore, which contains sea caves. The NPS Geologic Resources Division Cave and Karst Resources website, http://www.nature.nps.gov/geology/caves/index.cfm (accessed 10 April 2015), provides more information.

Sea caves are recent features carved into the ancient bedrock at Apostle Islands National Lakeshore. They formed in exposures of the Bayfield Group (**PCch**, **PCdi**, and **PCo**) and are somewhat limited in scope.

Figure 9. Ice caves and ice formations along shorelines. Significant ice accumulation leads to frost weathering of the bedrock outcrops and likely accelerates blockfall and erosion. These features are particularly popular with visitors and accessible when the lake surface freezes adequately. National Park Service photographs courtesy of Julie Van Stappen (Apostle Islands National Lakeshore), taken in January 2014.

Most are fairly shallow and close to the water's surface. The lakeshore restricts climbing in caves and bluffs (see "Caves and Associated Landscape Management" section). Sea caves are erosional features grouped with cliffs, embayments, rocky headlands, arches, stacks, windows, and wave-cut platforms, common along the rocky shores of the islands and Bayfield Peninsula (fig. 10). The type of feature created depends on the nature of the bedrock and the orientation of its exposure to the waves of Lake Superior. Sea caves typically form where less erosion-resistant layers, exposed at water level (fig. 11), 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. Lateral spreading of reentrants is particularly common in the thinly laminated, flat-bedded, flaggy sandstone of the Devils Island Sandstone (**PCdi**). Exposures can become honeycombed with cavities. Where Devils Island Sandstone is exposed along the shorelines at Sand Island, Devils Island, and at Mawike Bay cliffs, intricate systems of sea caves occur (Wright 1997; Nuhfer and Dalles 2004).

Joints (fractures in rock, commonly parallel) are nearly vertical in the Bayfield Group (**PCo**, **PCdi**, and **PCch**). These joints create localized zones of weakness, which are exploited by wave erosion and cause the rock faces

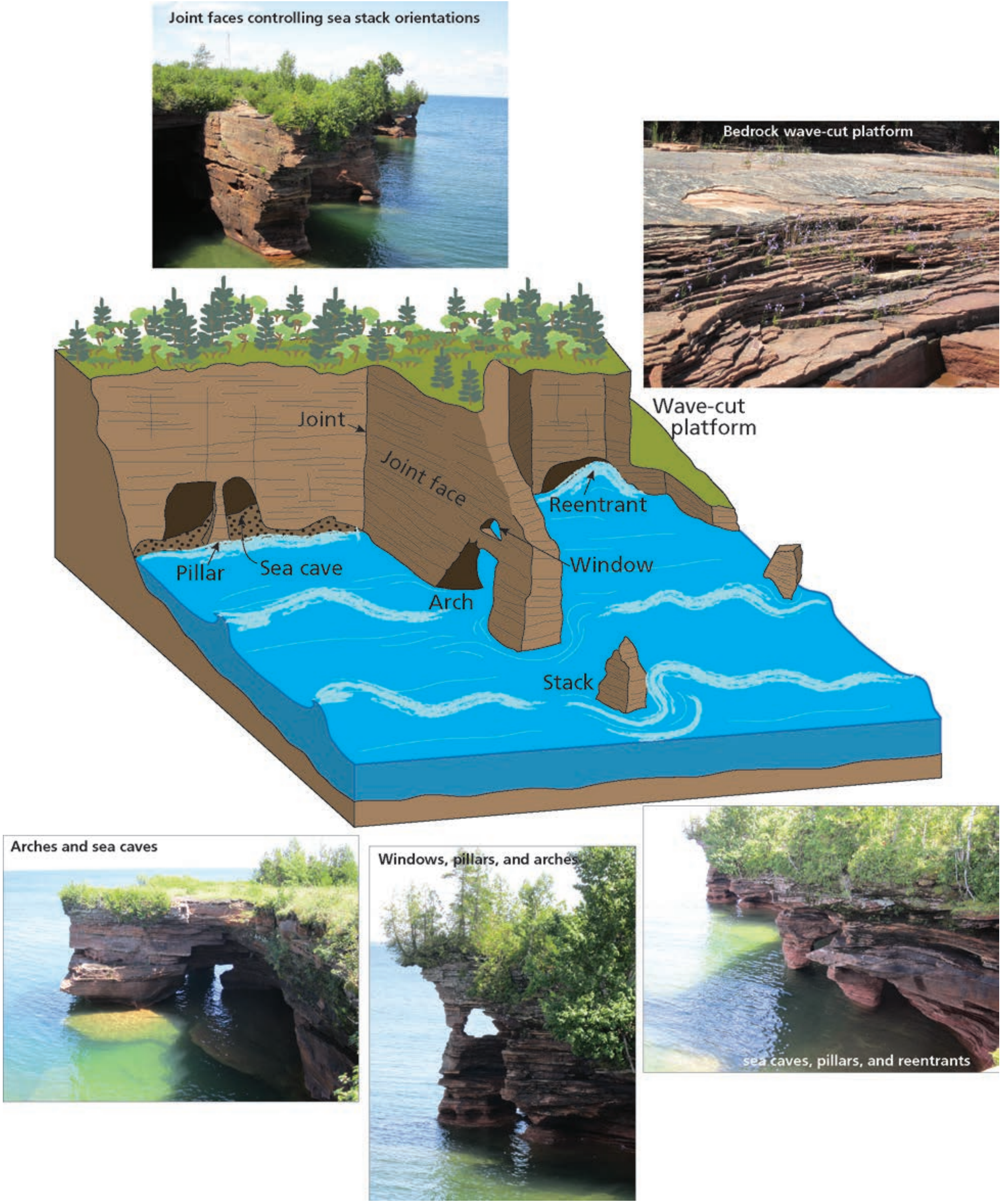


Figure 10. Bedrock erosional features on Devils Island. Waves from Lake Superior carve the rocky shorelines of Apostle Islands National Lakeshore into features such as reentrants, sea caves, arches, windows, platforms, and stacks. Photographs show some of these features throughout the lakeshore. Photographs by Trista L. Thornberry-Ehrlich (Colorado State University), taken in July 2010. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Nuhfer and Dalles (2004, figure 9).

Figure 11. Sea caves forming at water level. Waves from Lake Superior carve sea caves into the rocky shorelines of Apostle Islands National Lakeshore. Note the smooth indentations at other levels on the cliffs. These may be the outcome of differential erosion among rock layers or indicate former lake levels. Photograph by Hal Pranger (NPS Geologic Resources Division) taken in August 2005 along the mainland unit's shoreline on the northwestern side of the Bayfield Peninsula.

to retreat unevenly, producing a jagged shoreline with protruding spurs and undercut reentrants. Such a landscape is visible at the northeast corner of Stockton Island (Nuhfer and Dalles 2004). Additionally, joint orientations influence the formation of arches and stacks (see fig. 10). As a protruding spur of bedrock between joints is exposed to wave energy, an arch may be excavated. When enough of the spur material is removed, pillars or stacks of rock are isolated from the island and remain until falling or eroding away. Stack development is particularly evident at Eagle Island. Other stacks include "Honeymoon Rock" of the northern end of Basswood Island, and some pedestals on the northern end of Cat Island (Nuhfer and Dalles 2004).

Wave-cut platforms are also erosional shoreline features present at the lakeshore. They represent periods of relatively constant lake water elevations. Waves and cobbles rolled by the waves erode these platforms. Wave-cut platforms or benches 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 and are visible in exposures of the Chequamegon and Orienta sandstones (**PCch** and **PCo**) at Outer Island, Stockton, and North Twin islands (Nuhfer and Dalles 2004). The erosional, western shoreline of Rocky Island has wave-cut benches and a gradual, curving shore trace (Thornberry-Ehrlich 2013).

At the lake-to-land interface, most islands have some isolated splash pools or pools on cliff shelves. Dense systems of rock pools occur on the bedrock platform shores of Bear, Devils, and Stockton islands. As discussed in the "Geologic Significance and Connections" chapter, these pools host diverse chemical, biological, and ecological features (Lafrançois et al. 2010). Some of the pools are dominated by wave action and experience regular scouring. Interconnected splash pool zones are typically ephemeral with dry periods between rain or wave incursions. Some pools, particularly those closer to the islands' trees, experience less frequent wave impacts, are likely influenced and/or nourished by groundwater, and can support lichen growth. They are called lichen zone pools (Lafrançois et al. 2010).

In shoreline areas not underlain directly by bedrock, other shoreline erosion features form. Thick glacial tills underlie most of the Apostle Islands. Glacial-till bluffs form where waves are eroding into the thick, unconsolidated material deposited by the Pleistocene glaciers atop many of the Apostle Islands, including Stockton, Raspberry, Outer, and Sand islands. Erosion of these bluffs produces slumping and landslide scars (see "Slope Movements" 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).

Sandscapes

Among the most dynamic geologic features within Apostle Islands National Lakeshore are the sandscapes—collections of landforms (however temporary) composed of loose particles that are transported and reworked by wind and water (fig. 12). 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). In general, sand is transported in a southwesterly direction along the eastern and western sides of the islands and accumulates on the sheltered, southern or lee sides of

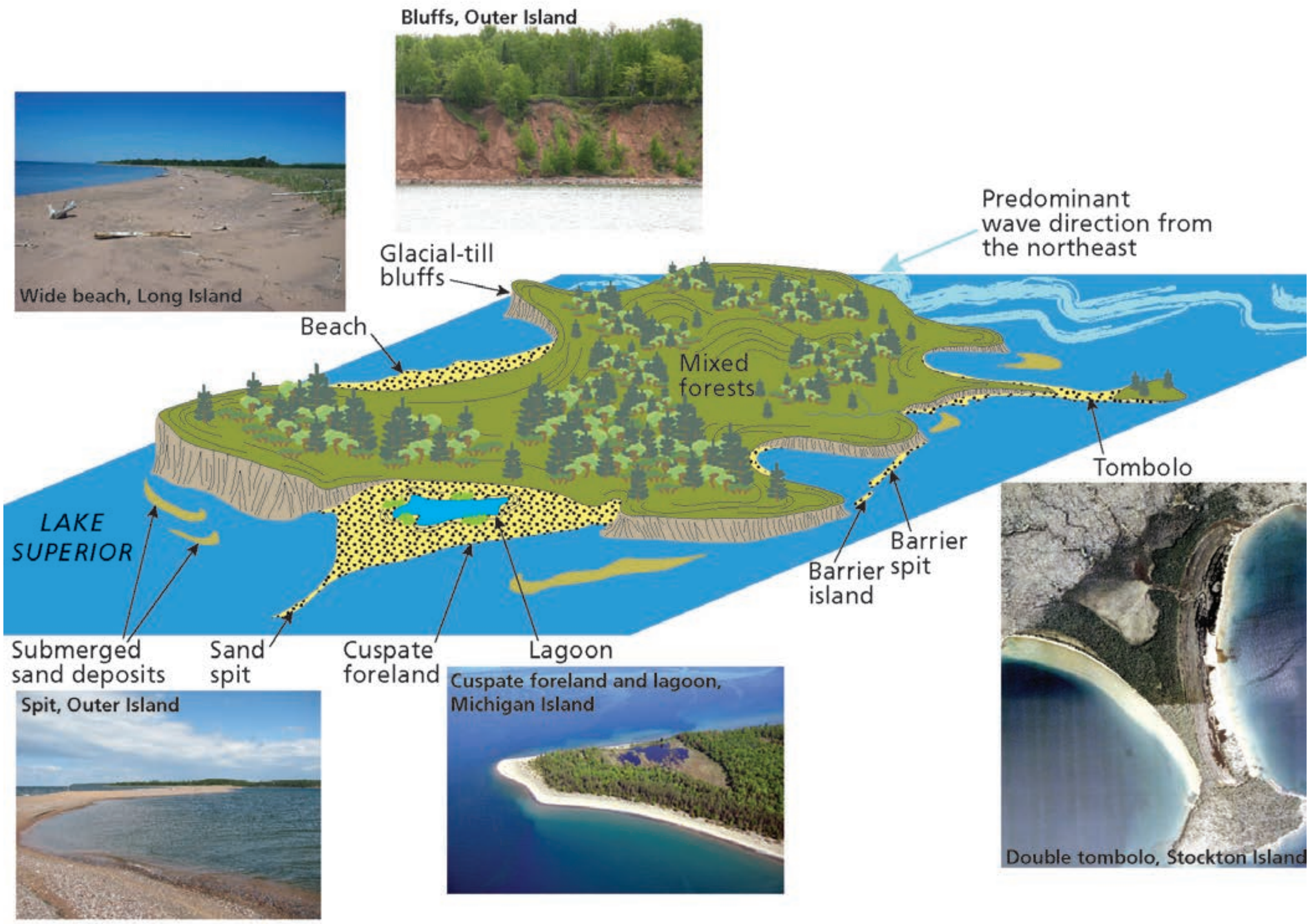


Figure 12. Sandscape formation. Sand deposits are weathered from glacial-till bluffs of the Apostle Islands. Waves and longshore currents transport the weathered material, depositing it in sheltered coves and leeward sides of the islands. Photographs show examples from the shorelines of Apostle Islands National Lakeshore. National Park Service photographs courtesy of Julie Van Stappen (Apostle Islands National Lakeshore). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Nuhfer and Dalles (2004, figure 8).

the islands (Engstrom 1985; Thornberry-Ehrlich 2013). Sandscapes at the Apostle Islands consist of beaches, sand spits, tombolos, cuspate forelands, barrier spits and islands, and dunes. They are mostly composed of postglacial deposits, shoreline sediment (**Qc**), which is weathered from glacial-till deposits such as the Miller Creek Formation (**Qgl** and **Qgw**) (Clayton 1984, 1985; Nuhfer and Dalles 2004). This sand supply affects the mean grain size of the sand (Engstrom 1974b).

Beaches

Beach configuration depends on wave conditions. Beaches form where waves have stacked sand onto the shoreline in protected coves where the sand circulates (fig. 12). Storm waves move sand from the beach to offshore bars leaving cobble-covered surfaces. By contrast, gentler waves move sand from the offshore bars onto the beach to form gently sloping beaches. Beach height is a function of wave energy and the direction of dominant wave approach; vigorous swash moves the sand further inland (Engstrom 1974a, 1974b). Lower wave energy may promote wider beaches (Engstrom 1974a, 1974b). The forebeach is the lakeward-sloping zone of the beach that is between the low-water mark and beneath the berm of sediment that marks the highest waves. It is frequently washed by waves (see fig. 16). Berms are low, impermanent benches or shelves formed landward of the forebeach composed of material transported and deposited by larger storm waves (see fig. 16).

Beaches that are particularly well developed occur at

Julian Bay and Presque Isle Bay at Stockton Island and on the northern side of York Island. Glacial-till bluffs provide nourishment for beaches at Sand Bay on the Bayfield Peninsula; Quarry Bay on Stockton Island; Lighthouse, Justice, and West bays on Sand Island; and a beach on the eastern side of Raspberry Island (Engstrom 1985; Nuhfer and Dalles 2004).

Sand Spits, Tombolos, and Cuspate Forelands

Sand spits, tombolos, and cuspate forelands (fig. 12) can be transitional (e.g., sandscapes change from one feature to another over time) or physically connected to each other. Sand spits (elongate "fingers" of sand) typically develop on the sides of islands leeward to the dominant wave direction. Sand spits are well developed on Outer, Michigan, Rocky, South Twin, and Cat islands (Nuhfer and Dalles 2004). If a sand spit grows and extends all the way to another island, connecting the two, it forms a tombolo. A double tombolo, where sand spits extended from two headlands toward each other, connects Stockton Island and Presque Isle Point, enclosing a lagoon. This tombolo formed where wind and wave action accumulated sand between the formerly separated islands. The reddish sand is probably from the Miller Creek Formation, (**Qgh**, **Qgl**, and **Qgw**). The tombolo itself has beaches, dunes, and washover fans.

The Holocene sand (**Qc**), juxtaposed against the Mesoproterozoic Chequamegon Sandstone (**PCch**) represents more than a billion years of geologic time at a tangible unconformity. Cuspate forelands are broad, crescent-shaped landforms often projecting off the leeward side of an island to the dominant wave direction. Examples of cuspate forelands appear on Bear, Raspberry, Ironwood, Oak, Otter, South Twin, and Stockton islands (Nuhfer and Dalles 2004; Thornberry-Ehrlich 2013).

Barrier Spits and Islands

Barrier spits and islands (fig. 12) require abundant sand and strong longshore currents (fig. 13). A large, 6.7-ha (16.5-ac) sand spit, containing a freshwater lagoon, occurs off the southeastern end of Outer Island. Rocky and Michigan islands have 2-ha (5-ac) and a 3-ha (7.5-ac), lagoon-trapping cuspate forelands (fig. 14; Thornberry-Ehrlich 2013). Long Island is the most prominent example of a barrier spit and island at Apostle Islands National Lakeshore. It is a long, narrow barrier trending northwestward into the mouth of Chequamegon Bay. It features a complex of parallel beach rides and adjacent bog-filled swales (Bona 1990; Bona and Kiesel 1990). It is

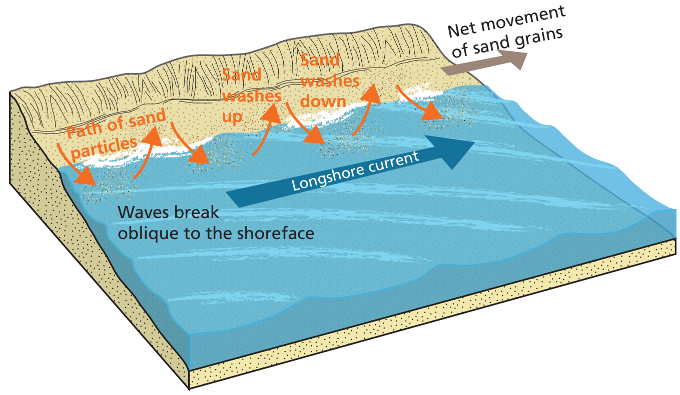


Figure 13. Longshore drift. Sand grains are transported by waves and longshore currents to be deposited in sheltered coves and leeward sides of the islands. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Capital Regional District graphic at https://www.crd.bc.ca/education/in-your-community/geology-processes/coastal-sediment (accessed 9 September 2014).

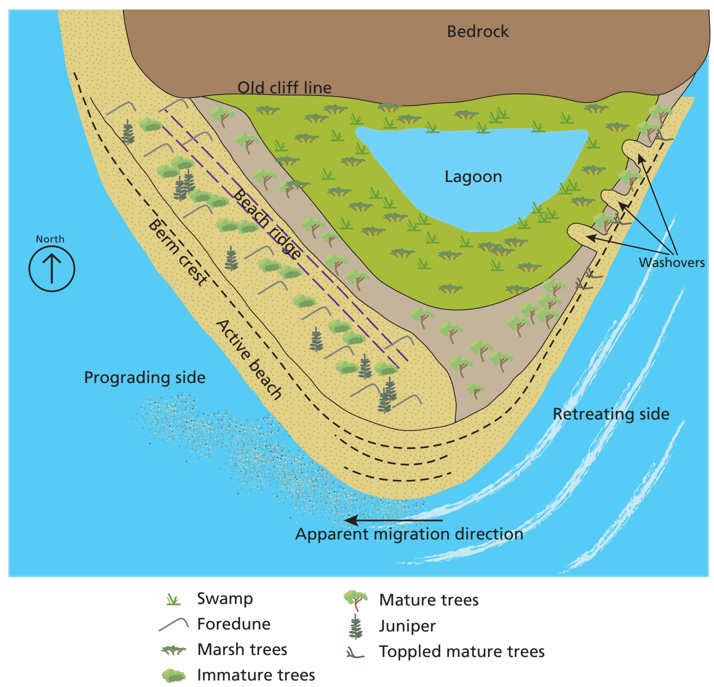


Figure 14. Model cuspate foreland. Plan view of a cuspate foreland off the southern shore of an Apostle Island. As sand is transported from the waveward to the leeward side of the island, the cuspate foreland retreats. Note the changes in vegetation from one area to another. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Engstrom (1985, figure 2).

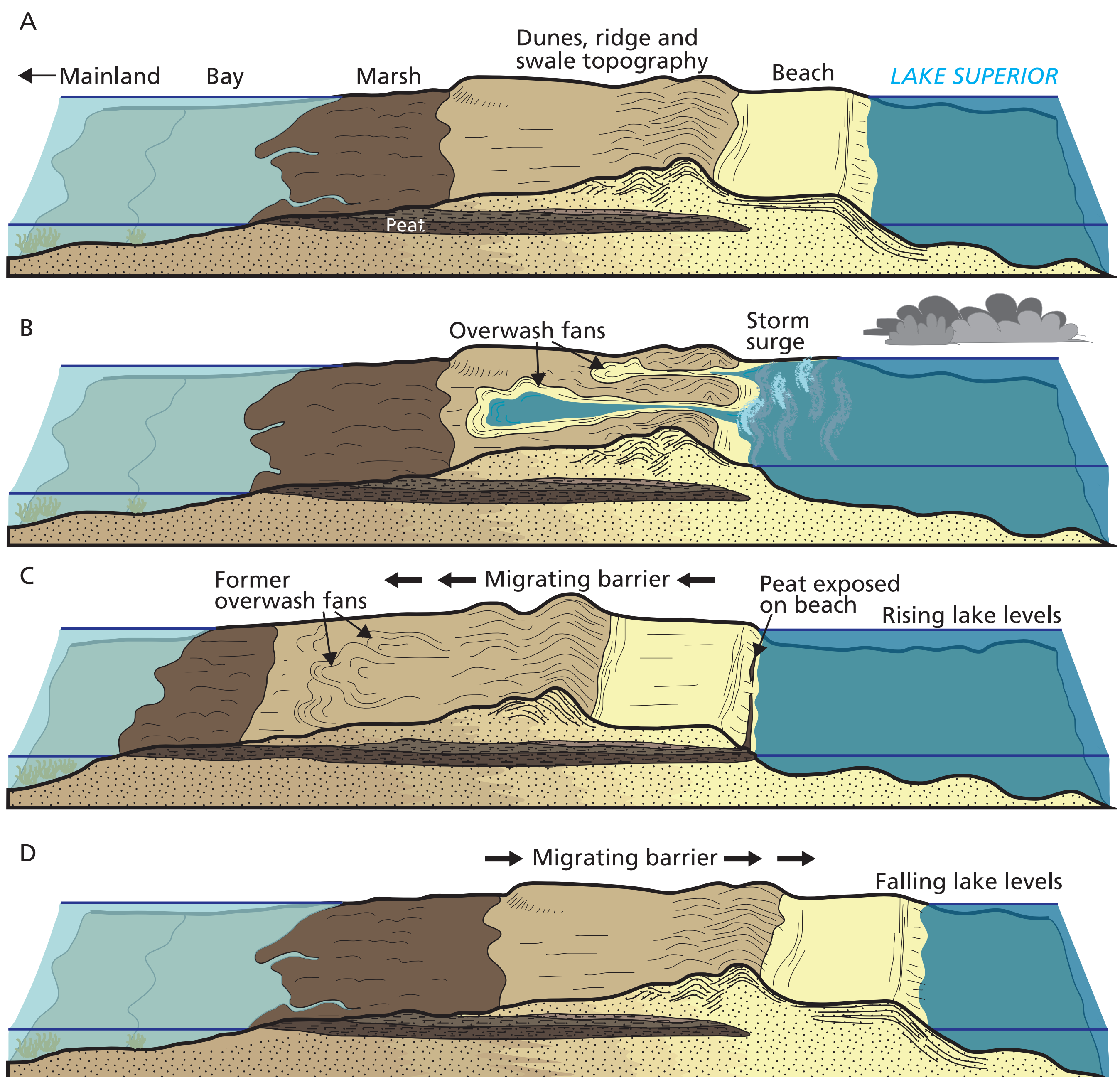


Figure 15. Barrier island migration. At Apostle Islands National Lakeshore, barriers composed of unconsolidated sediment display a characteristic array of features spanning from the open lake, up a beach front, through dunes and ridges, across a marsh, and to the bay toward the mainland (A). Overwash transports sand onto and across the island (B). Over time, with rising lake levels, the island migrates landward, building on top of the old marsh (C). If lake levels fall, the opposite occurs as the barrier migrates lakeward (D), which is currently the case of Long Island. However, no peat is exposed on the lakeshore of Long Island (Julie Van Stappen, written communication, 9 January 2015). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

the only island in the lakeshore composed entirely of unconsolidated deposits (**Qc**). It lacks a bedrock core, which on other islands stabilizes sand deposits. The sand of Long Island is susceptible to barrier movement as a response to storms and variable longshore currents (Bona 1990; Bona and Kiesel 1990). Long Island formed as northeastward-flowing streams, such as the Kakagon and Bad rivers, transported sand onto the southern shore of Lake Superior. The sand was then carried northwestward by longshore currents of the lake (Nuhfer and Dalles 2004). The last dramatic change for Long Island occurred in November 1975

Figure 16. Dune and beach features at Stockton Island of Apostle Islands National Lakeshore. Clockwise from the upper left: wide beach area with foredunes in the background, sea grass stabilizing dune areas, a sand blowout resulting from a windstorm threatens the integrity of a boardwalk trail, and beach berm fronting a narrow forebeach. Photographs by Trista L. Thornberry-Ehrlich (Colorado State University; upper and bottom right; taken in July 2010) and Hal Pranger (NPS Geologic Resources Division; bottom left; taken in August 2005).

as a large storm—the same storm that sank the SS *Edmond Fitzgerald*, the largest ship to have sunk on the Great Lakes—connected a series of sand bars into the large spit that persists today (Ojakangas et al. 2011). The barrier spit is currently migrating lakeward, and the southern side is somewhat stabilized by vegetation (Bona 1990; Bona and Kiesel 1990). Geologists expect the barrier to be breached in a storm forming a true barrier island once again (fig. 15; Thornberry-Ehrlich 2013).

Dunes

Dunes are less common and much smaller than other sandscapes at Apostle Islands National Lakeshore (figs. 16 and 17; see “Aeolian Processes” section). Rocky Island’s sandscapes include foredunes and ridge and swale complexes on the eastern shore (Thornberry-Ehrlich 2013). Foredunes are sand ridges oriented parallel to the shoreline that occur at the landward margin of a beach area (fig. 16). Excellent examples of foredunes occur at Stockton Island, where many are stabilized by vegetation. The double tombolo between Stockton Island and Presque Isle has the second largest dune area in the lakeshore. Long Island has 2.4 km (1.5 mi) of active dunes (Thornberry-Ehrlich 2013).

Postglacial (Recent) Surficial Deposits

Surficial deposits—including shoreline sediments, organic sediment, and stream (fluvial) sediment (**Qc**, **Qp**, and **Qsm**, respectively; see Map Unit Properties Table, in

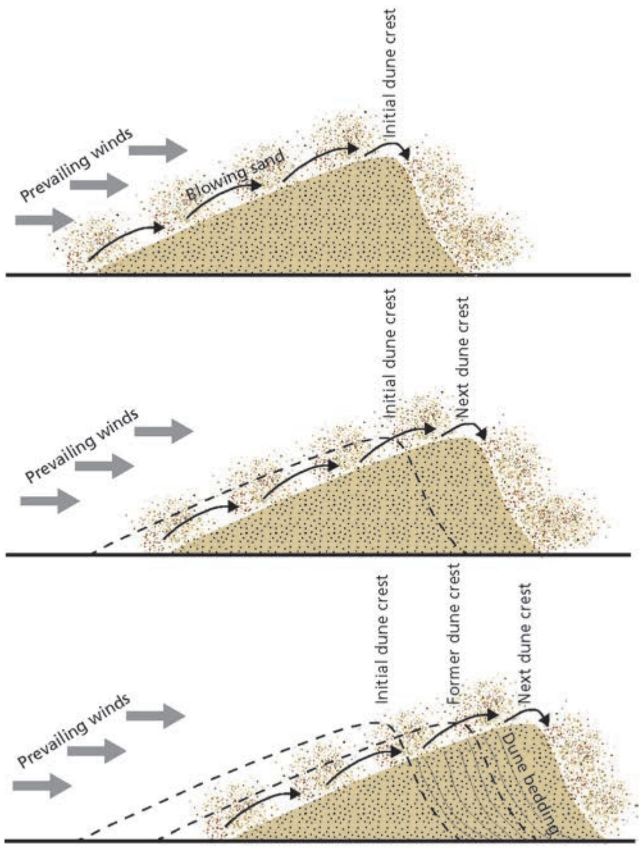


Figure 17. Aeolian sand transportation and dune movement. Prevailing winds transport sand grains up the dunes, depositing them in cascades down the steep side. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

pocket)—are constantly being deposited and reworked on the Apostle Islands' landscape. As described in the "Sandscapes" section, shoreline sediment (**Qc**) fringes much of the dynamic shoreline at the lakeshore. Long Island is composed of this unit. Organic sediments (**Qp**), including peat, are collecting in lagoons and marshes at the lakeshore. These are useful for dating purposes because they contain organic carbon and fossil pollen records (see "Paleontological Resources" section). As described in the "Fluvial Features" section, stream sediments (**Qsm**) are collecting along local streams and rivers within the lakeshore. They are mapped at the mouth of the Sand River (Clayton 1985).

Fluvial Features

Many rivers that flow into Lake Superior near the Apostle Islands contribute to the lakeshore ecosystem. Sand, Siskiwit, Raspberry, Sioux, Kakagon, Bad, Montreal, and White rivers, and North Fish, South Fish, Red Cliff, Pikes, Saxine, Squaw, and Beartrap creeks are among the larger waterways. Bayfield Peninsula streams can transport upwards of 40 million kg (44,000 tons) of suspended sediment to Apostle Islands National Lakeshore area per year (Rose 1987).

Rose (1987) inventoried the water resources of Apostle Islands National Lakeshore and noted that few island streams flow perennially; most are ephemeral. Oak and Stockton islands have some streams with year-long base flows dominated by groundwater discharge and seepage from wetlands and beaver ponds, respectively. Smaller islands such as York, Raspberry, Eagle, Devils, South Twin, North Twin, Gull, and Ironwood have virtually no distinguishable surface drainage channels.

The Sand River, which flows through the mainland unit, is the primary fluvial feature within the lakeshore (Rose 1987; Thornberry-Ehrlich 2013). Several of the larger rivers reach the lake forming a wetland, estuary, or slough. The delta at the mouth of the Sand River is an estuary-like area with a sand spit, bogs, and some low-level terraces flanking the river channel (Thornberry-Ehrlich 2013). These features are composed of stream sediment (**Qsm**). The Sand River valley was carved before the deposition of the Pleistocene Miller Creek Formation (**Qw**, **Qb**, **Qgh**, **Qgl**, **Qgw**, and **Qou**). During glaciations, it was filled with sediment then became re-excavated to create the modern river valley. A similar situation exists for Fish Creek and the Sioux River gorge (Ojakangas et al. 2011). Besides the Sand River, the smaller streams within the lakeshore, for example, Raspberry River and Red Cliff Creek, are generally short (less than 2 km [1 mi]), with steep gradients, and small drainage areas (Rose 1987).

The evolution of local drainages has impacted the development of the sediment supply system for the Apostle Islands. Approximately 800 years ago, the White River captured the flow of the Bad River increasing the sediment supply to the Long Island barrier spit system (Ojakangas et al. 2011). The Bad and Kakagon rivers were once joined, and the sediments they transported to Lake Superior supplied the estuary system on the western side. As described in "Sandscapes" section, these sediments contributed to the formation of Long Island. Today, the rivers are separated and Bad River enters the lake on the east side of the Kakogan-Bad River Slough—the largest undeveloped wetland system on the Great Lakes (Tynan 2012). Local predominant longshore movement is to the east, now supplying sediment to Waverly Beach (Ulf Gafvert, Julie Van Stappen, and Peggy Burkman, conference call, 19 June 2014).

Glacial Features

During the Pleistocene Epoch (2.6 million to 11,700 years ago; fig. 3), climate alternated between glacials (ice ages) and interglacials (warm periods similar to modern climate). Black (1974) described the glacial deposits and history of Wisconsin—the namesake of the Wisconsinan glaciation, the most recent of the four major recognized ice-age events of the Pleistocene Epoch. Repeated glaciations scoured and reshaped the landscape of the northern United States, including Apostle Islands National Lakeshore, when massive ice sheets advanced from the Arctic (fig. 18). As the glacial lobes descended into the Great Lakes area and beyond, they became progressively thinner with distance from their source. Locally, the Superior Lobe was some 400 m (1,300 ft) thick, a massive quantity of ice but only half of its maximum thickness farther north (Thornberry-Ehrlich 2013).

The two major categories of glacial features at Apostle Islands National Lakeshore are (1) those created or carved by glacial ice, and (2) those deposited by meltwater, either "glaciofluvial" (deposited by rivers flowing beneath or out of glaciers) or "glaciolacustrine" (deposited in lakes near glaciers). Figure 19 provides schematic illustrations of these features. Features associated with glacial ice include till, moraines, drumlins, kettles, grooves, striations, roches moutonnées, and glacial erratics. Glaciofluvial and glaciolacustrine features include kames; eskers; braided streams; and outwash fans, deltas, or plains.

Investigators mapped two prominent glacial units on the Bayfield Peninsula and Apostle Islands—the older glacial till and outwash of the Copper Falls Formation (**Qsc**, **Qsg**, **Qsu**, **Qsuc**, and **Qgg**) dating back to 11,500 years before present, and the younger lacustrine and glacially reworked sediments of the finer-grained Miller Creek Formation (**Qw**, **Qb**, **Qgh**, **Qgl**, **Qgw**, and **Qou**), deposited between 11,500 and 9,500 years before present (Clayton 1984; Ojakangas et al. 2011).

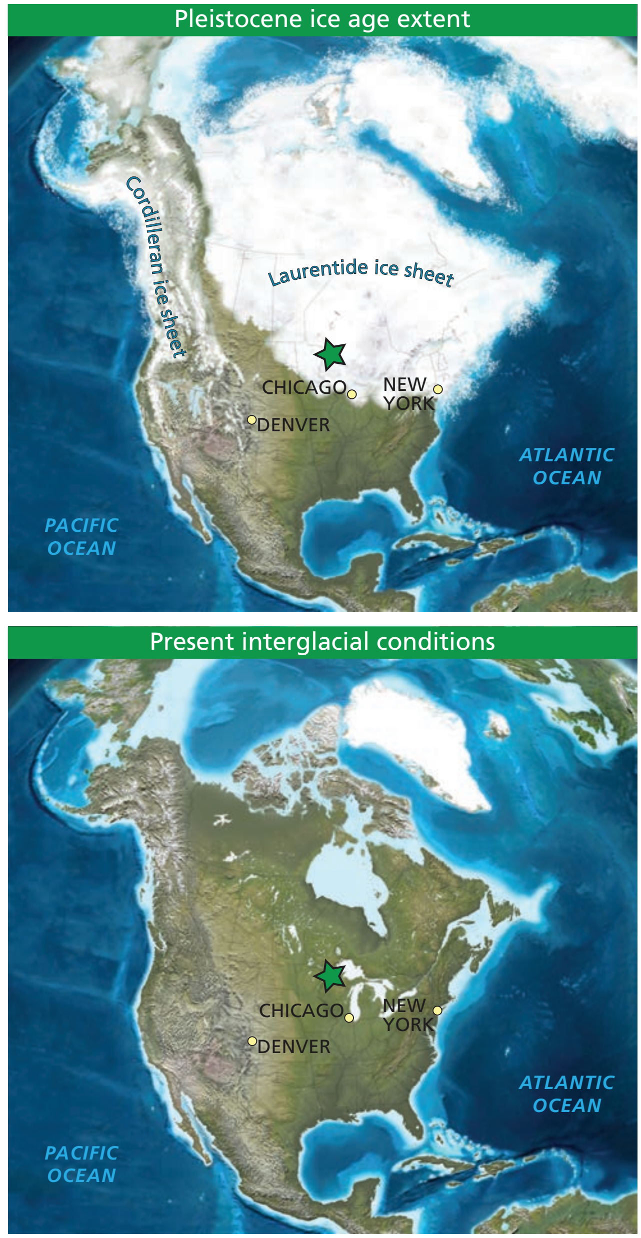


Figure 18. Comparison of Ice-age and interglacial conditions. Nearly half of North America was covered by ice during Pleistocene glaciations. Relative sea level dropped during glaciations (note the expanded width of Florida [white shading]). The location of Apostle Islands National Lakeshore is denoted by a green star. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), produced using base paleogeographic maps created by Ron Blakey (Colorado Plateau Geosystems, Inc.), available at http://cpgeosystems.com/index.html (accessed 2 July 2014).

Glacial Landforms

Perhaps the greatest examples of local, glacially influenced landforms are the Apostle Islands themselves. As the glaciers descended southward, they flowed preferentially through topographic lows such as stream valleys. In the Apostle Islands National Lakeshore area, the Bayfield Peninsula was a

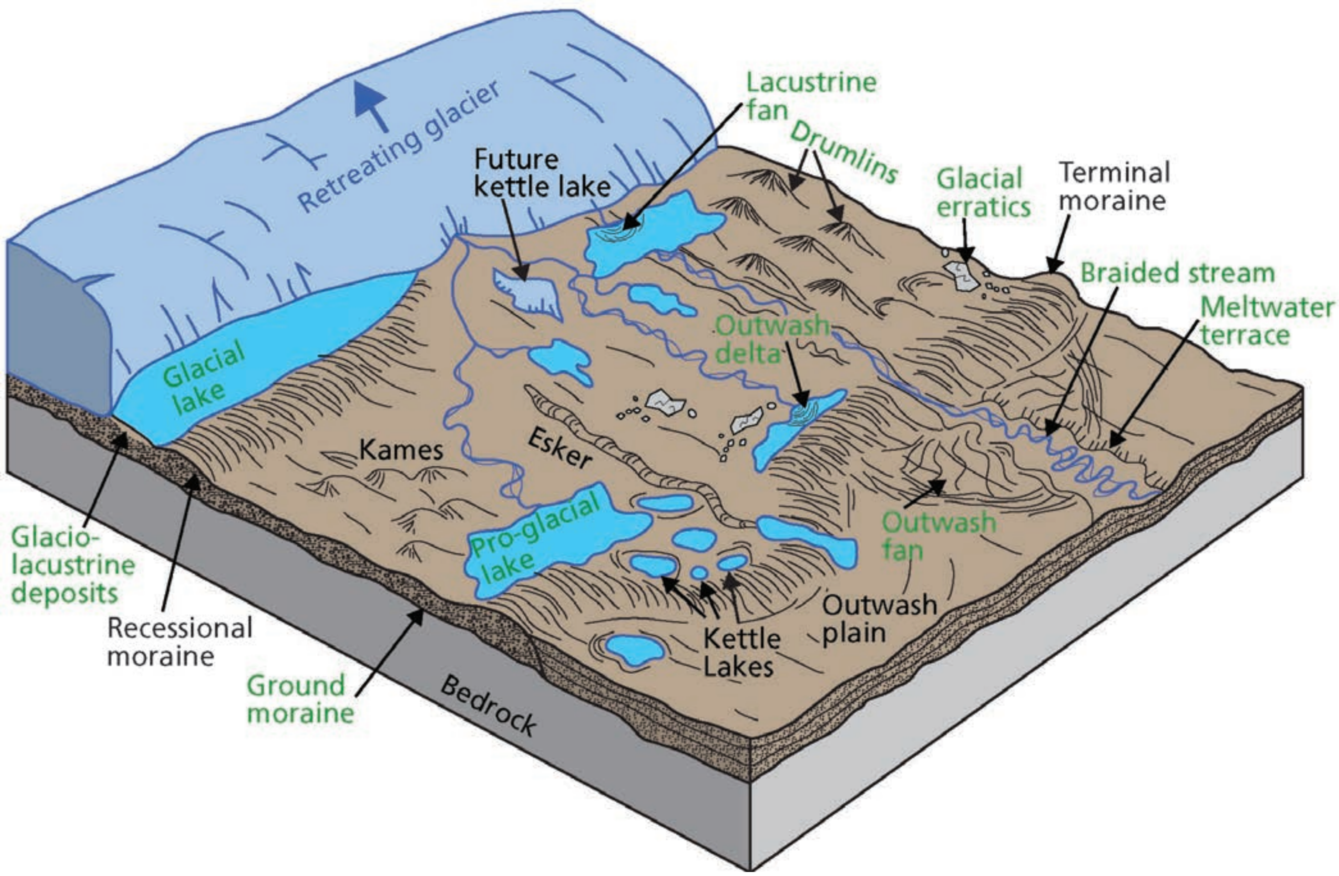


Figure 19. Glacial features. Not every glacially-altered landscape contains all of these features or deposits. Prominent features and deposits within Apostle Islands National Lakeshore are labeled in green and include lacustrine fans, drumlins, glacial erratics, glaciofluvial deposits, outwash fans, outwash deltas, glaciolacustrine deposits, kames, and glacial grooves and striations (see fig. 19), and. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

topographic high composed of resistant Precambrian bedrock (**PCo**, **PCf**, **PCdi**, and **PCch**). The peninsula posed an impediment to glacial flow and split the glacier into two lobes, the Superior to the south and west, and the Chippewa to the east (fig. 20). Thick, coarse-grained sands and glacial deposits collected between the lobes down the axis of the Bayfield Peninsula (Ojakangas et al. 2011). When the ice retreated to the north and Lake Superior filled with water, the resistant remnants of sandstone at the flanks of the ancient Midcontinent rift were left as islands sheltered by the Bayfield Peninsula.

Mapped features associated with moving glaciers, part of the GRI GIS data, include drumlins, glacial ice-movement directions, and glacial ridges. Drumlins are elongated linear hills that formed when a glacier flowed over a mass of sediment (fig. 21). They are mapped (Glacial Feature Lines in GRI GIS data; see table 3) on Stockton, Outer, Cat, Michigan, and Devils islands, as well as on the Bayfield Peninsula and Madeline Island. Primarily oriented northeast–southwest, drumlins indicate the direction of glacial movement in the area (Clayton 1984, 1985). Glacial grooves and striations also record the direction of ice movement as rocks entrained at the base of a glacier are scraped over the underlying bedrock. Stockton and Bear islands have excellent examples of glacial grooves (Nuhfer and Dalles 2004).

Glacial Deposits

Glaciers deposit all sorts of sediment and create a variety of landforms (see fig. 19). As described in detail in the Map Unit Properties Table and the "Geologic History" section, glacial deposits in the area of present-day Apostle Islands include those deposited directly by moving ice and those deposited by meltwater in rivers or lakes. Such features and deposits are significant in the mapped area. Clayton (1984, 1985) provided detailed glacial histories and feature descriptions for the Apostle Islands area.

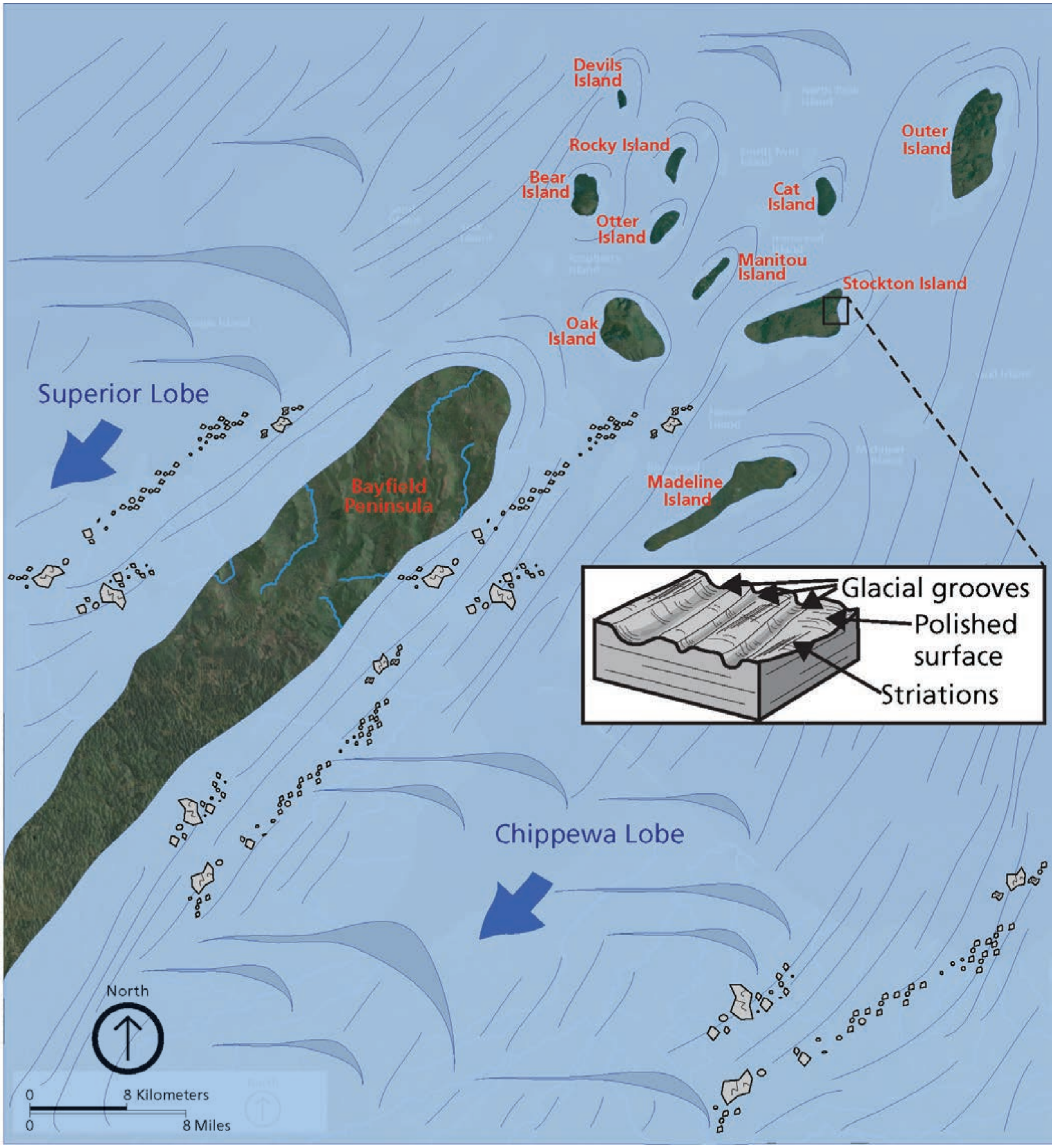


Figure 20. Bayfield Peninsula during glaciation. The Bayfield Peninsula split the descending glacier into two distinct lobes—the Superior Lobe to the south and west, and the Chippewa Lobe to the east. Glaciers flowed in valleys between prominent knobs of bedrock that became the Apostle Islands. Location of glacial ice is approximated; the actual Pleistocene ice extent was much farther south (see fig. 36) to near St. Louis, Missouri (Richard Ojakangas, University of Minnesota Duluth, geologist, written communication 12 January 2015). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with assistance from Georgia Hybels (Colorado State University).

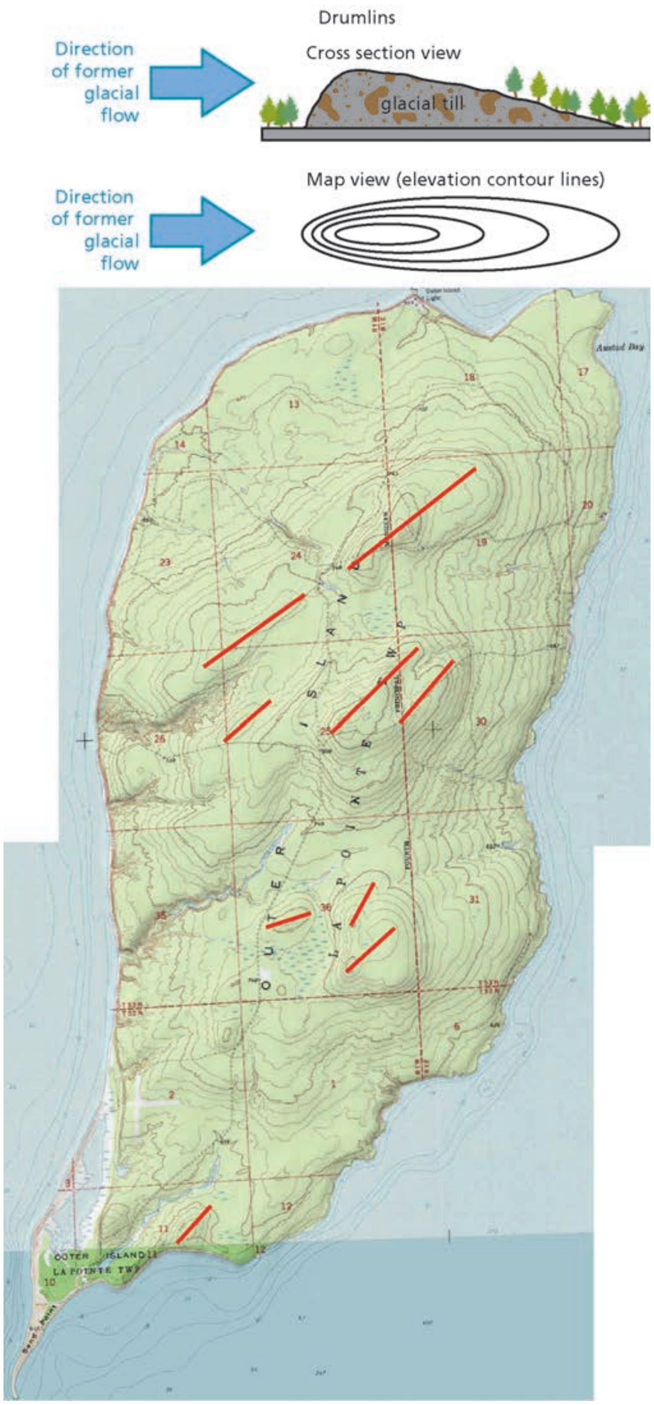


Figure 21. Drumlin formation. Drumlins are low, smoothly rounded, elongate oval hills that are formed by the movement of a glacier atop previously deposited glacial till. The long axis of the drumlin is parallel to the direction of glacial ice movement. Drumlin locations in Apostle Islands National Lakeshore are indicated in the GRI GIS data and displayed here for Outer Island (red lines). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with US Geological Survey topographic map coverage available from ESRI online.

Deposits associated with moving ice, and captured in the GRI GIS data, include reddish, loamy till from both the Miller Creek (**Qgh**, **Qgl**, and **Qgw**) and older Copper Falls (**Qgg**) formations. Glacial till (a mixed assortment of sediments deposited directly from glacial ice) mantles much of the bedrock in and around the Bayfield Peninsula, Apostle Islands, and Lake Superior itself. Within the lakeshore, only the Miller Creek Formation (**Qgl** and **Qgw**) is mapped. The Copper Falls Formation appears farther inland (Clayton 1984, 1985). The clay layers within the Miller Creek Formation act as aquicludes (rock bodies that confine groundwater) among more permeable layers. The buried Copper Falls Formation acts as a confined aquifer in the lakeshore. Its recharge area is at the height of the Bayfield Peninsula axis. Numerous artesian wells and springs occur throughout the Chequamegon Bay area (Ojakangas et al. 2011).

The 1- to 46-m- (2- to 150-ft-) high, reddish bluffs, characteristic of the western sides of several Apostle Islands, such as Michigan, York, Bear, Oak, Raspberry, and Outer, are mostly glacial till (Nuhfer and Dalles 2004). Some till forms moraines (ridges of material that mark the edges of a glacier). Terminal moraines, also called “end moraines,” mark the farthest advance of a glacier and help determine the extent of various glacial advances (see “Geologic History” section). The most conspicuous terminal moraines are located south of the Bayfield Peninsula (Peterson 1986). Glacial erratics (rocks transported some distance by a glacier that now rest upon bedrock of a different type) occur on many Apostle Islands. A notable example is a greenstone boulder, likely plucked from Canadian bedrock, discovered on the edge of the tombolo at Stockton Island (Thornberry-Ehrlich 2013).

Glaciolacustrine deposits are common in the map area and are associated primarily with previous stages of Glacial Lake Duluth and later, Lake Superior. Unlike glacial till, these sediments tend to have more rounded clasts and be well sorted with respect to grain size (Nuhfer and Dalles 2004). The glaciolacustrine layers tend to be clay rich, varved, and interbedded with other glacial deposits and some wave-worked glacial till. Clay-rich, glaciolacustrine deposits occur on the highlands of some islands, including Raspberry Island (Thornberry-Ehrlich 2013). Repeated glacial advances over the area “smeared” the deposits together like peanut butter on bread (Ulf Gafvert, Julie Van Stappen, and Peggy

Burkman, conference call, 19 June 2014). The GRI GIS data differentiate a variety of shoreline sediment, offshore sediment, lake-modified topography, wave-planed topography, and stream sediment units (see Map Unit Properties Table, in pocket, and "Geologic Map Data" section).

Glacial Lake Stages and Holocene Lake-Level History

When glacial ice retreated from the Lake Superior basin for the last time, approximately 9,900–10,000 years ago, lake levels fluctuated as a function of several factors: climate, isostatic rebound, outlet incision, and sedimentation (Blewett 2006). Lake levels fluctuated dramatically as various outlets were first exposed by deglaciation and then abandoned as they isostatically rose above other outlets (Pranger 2005). As described in the "Geologic History" section, meltwater ponded and many water-level stages of Lake Superior left features on the Apostle Islands landscape as a result of successive glacial retreats. Wave-cut terraces and benches mark these former highstands in a record of now-stranded shoreline features such as beach deposits (visible at Outer, South Twin, Oak, and Rocky islands), and wave-cut benches (visible at Oak and Bear islands) (Nuhfer and Dalles 2004).

Understanding the nature and timing of these major fluctuations is complicated due to the relatively small scale of the features involved (Blewett 2006) and the post-glacial erosion of features. The natural resource staff at Apostle Islands National Lakeshore would like additional information regarding the lake level history. High-resolution topographic and bathymetric data will reveal subtle wave-cut terraces, benches, and submerged shorelines (Ulf Gafvert, Julie Van Stappen, and Peggy Burkman, conference call, 19 June 2014). Analysis of the data may be a project for a Geoscientists-In-the-Parks Program participant. Such a map sheet was prepared for Crater Lake by Robinson et al. (2012), which may be a useful resource.

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 22 shows schematic illustrations of slope movements. Slope movements create geologic hazards and associated risk throughout the National Park System. Hazards and risks associated with slope movements in Apostle Islands National Lakeshore are described in the "Slope Movement Hazards and Risks" section.

Slope processes at Apostle Islands include sheetwash and runoff, slumping, liquefaction and mudflow, undercutting by seeps and springs, and undercutting by waves causing collapse, topple, and rockfall (Nuhfer and Dalles 2004). 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. 22). The bedrock shorelines are most prone to topple, blockfall, slides, or collapse of sea arches and stacks.

The glacial-till bluffs at Apostle Islands Lakeshore are particularly prone to slope movements such as translational and rotational slides, debris flows, and creep. Anderson (2003) recognized that the stability of the glacial till bluffs along the Wisconsin Lake Superior shoreline is controlled by the average slope angle, bluff composition (particularly cohesiveness), amount of water in the bluff, and amount and type of vegetation cover. The Miller Creek Formation (**Qw**, **Qb**, **Qgh**, **Qgl**, **Qgw**, and **Qou**) is notorious for its instability, particularly in areas where oversteepened and/or undercut by erosion or excavation (Ojakangas et al. 2011). Notable slumps occur at Michigan Island Light and Raspberry Island (fig. 23). The glacial-till banks tend to erode vertically where a more resistant glaciolacustrine clay layer caps the deposit (see "Glacial Features" section). The resistant layer supports a columnar-shaped pillar or "hoodoo" (fig. 24) of eroding glacial till (**Qgl** and **Qgw**) at places such as Outer and Raspberry islands (Ulf Gafvert, Julie Van Stappen, and Peggy Burkman, conference call, 19 June 2014).

Sedimentary Rock Features

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

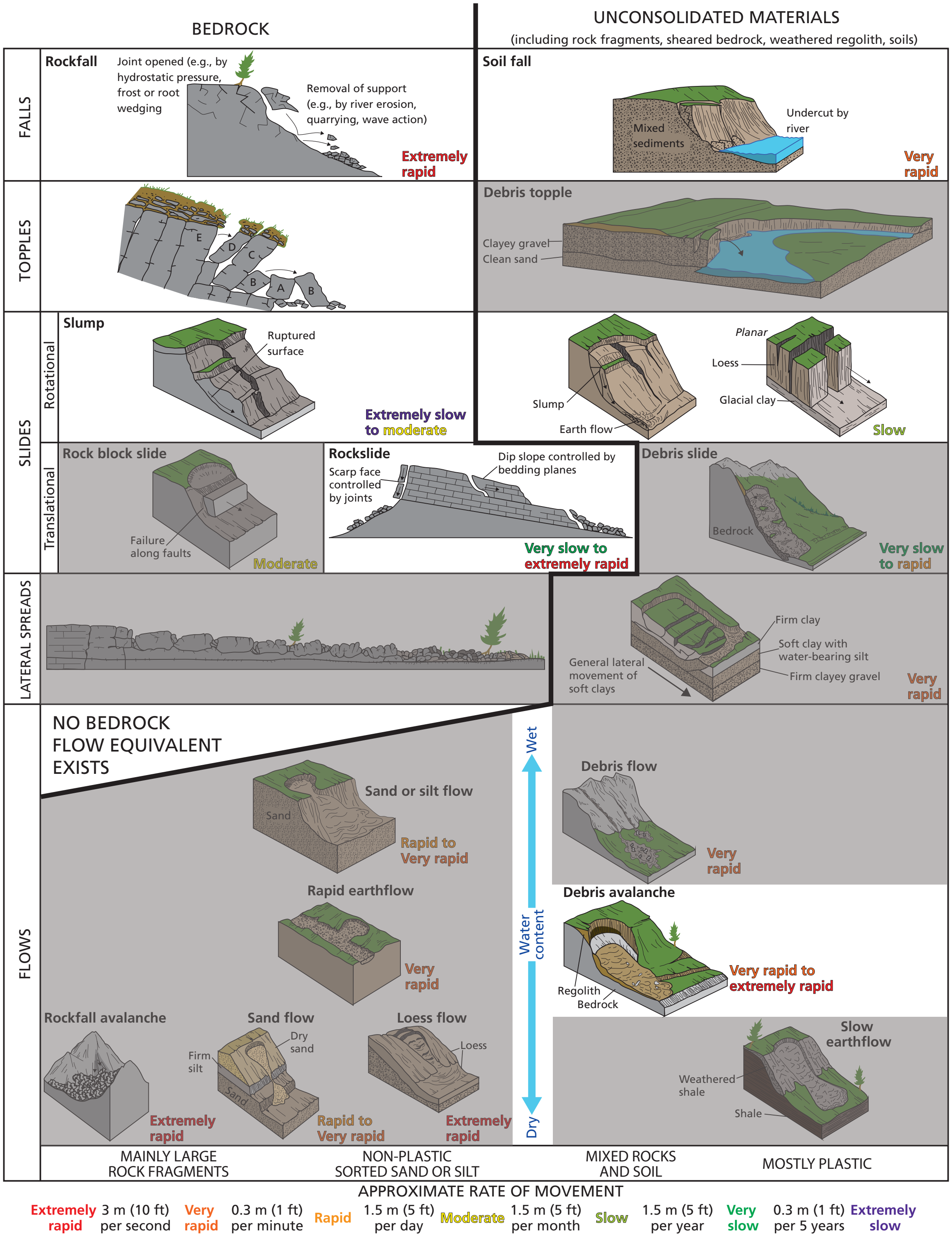


Figure 22. Schematic illustrations of slope movements. Different categories of slope movement are defined by material type, nature of the movement, rate of movement, and moisture content. Gray-shaded areas depict slope movements that are not likely to occur in Apostle Islands National Lakeshore. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Varnes (1978, figure 4.33 and information therein).

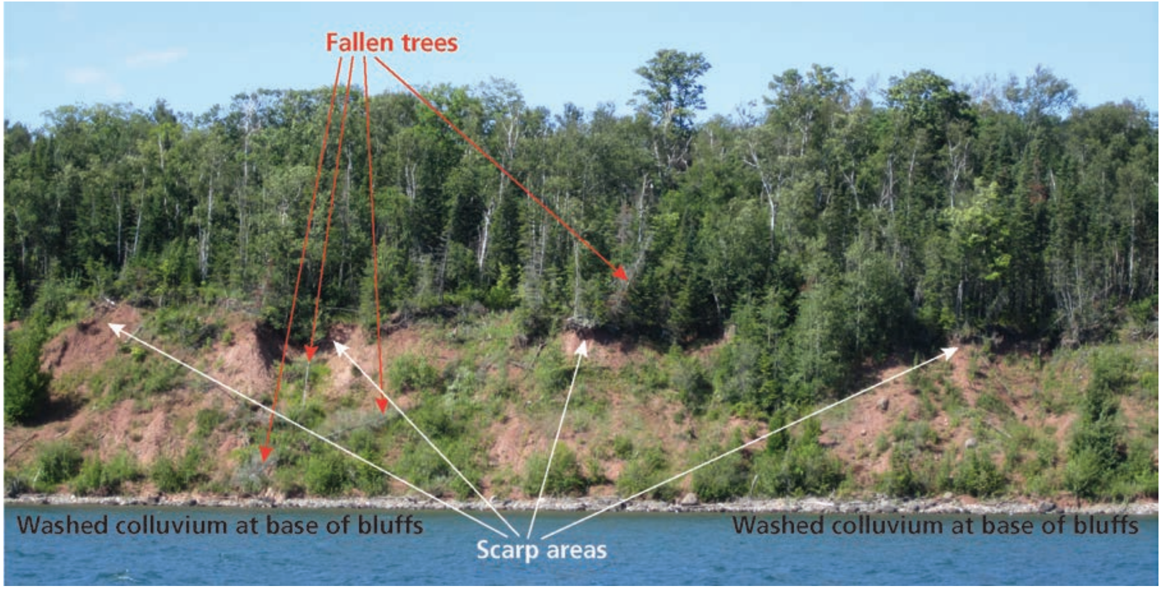


Figure 23. Eroding glacial-till bluffs at Raspberry Island. Note the slump scarps and vegetation sliding downslope. At the base of the slope, the finer material has been removed by the longshore current and wave activity, leaving gravel and boulders. The finer material provides sediment to the sandscape system. Photograph by Trista Thornberry-Ehrlich (Colorado State University) taken in July 2010.

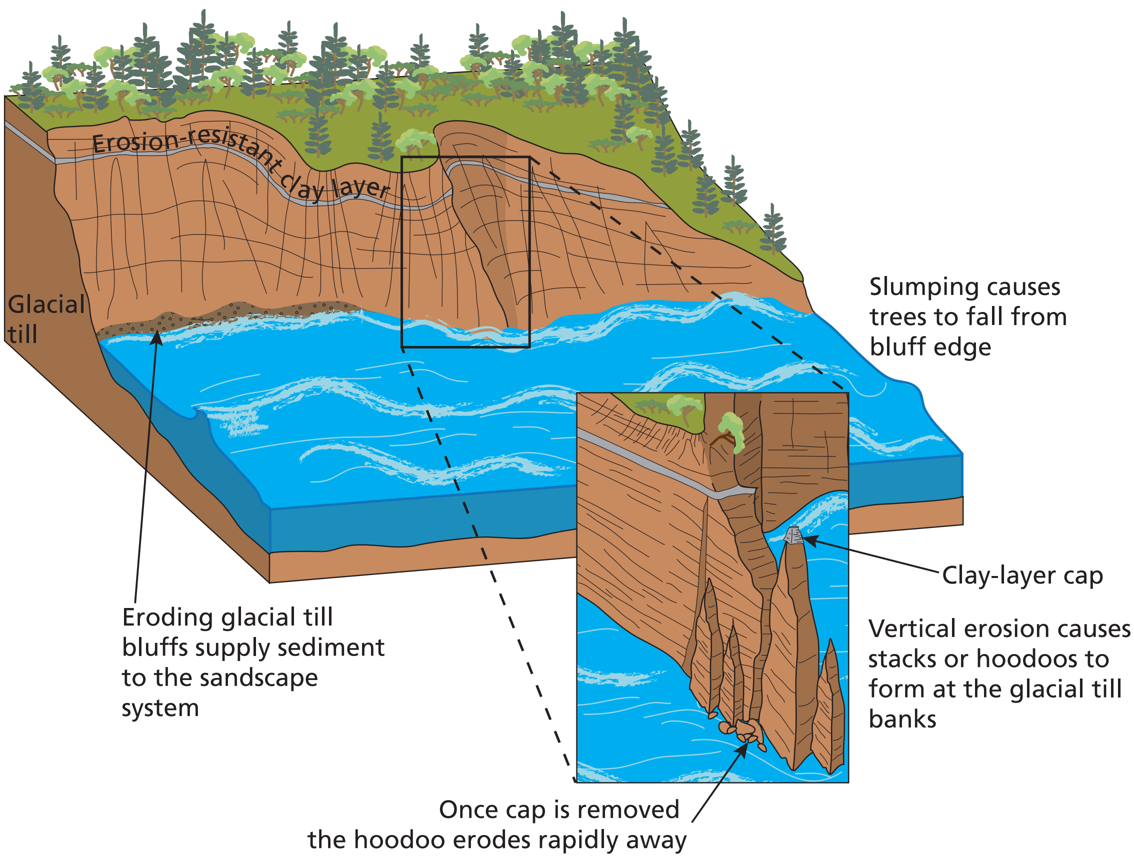


Figure 24. Eroding glacial-till bluffs into hoodoo-like forms. The formation of hoodoo-like vertical stacks along the glacial-till bluffs in places such as Raspberry Island requires a resistant cap of fine-grained clay. The cap temporarily protects the underlying column, but once the cap is breached, the unconsolidated material erodes quickly away into the waves of Lake Superior. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

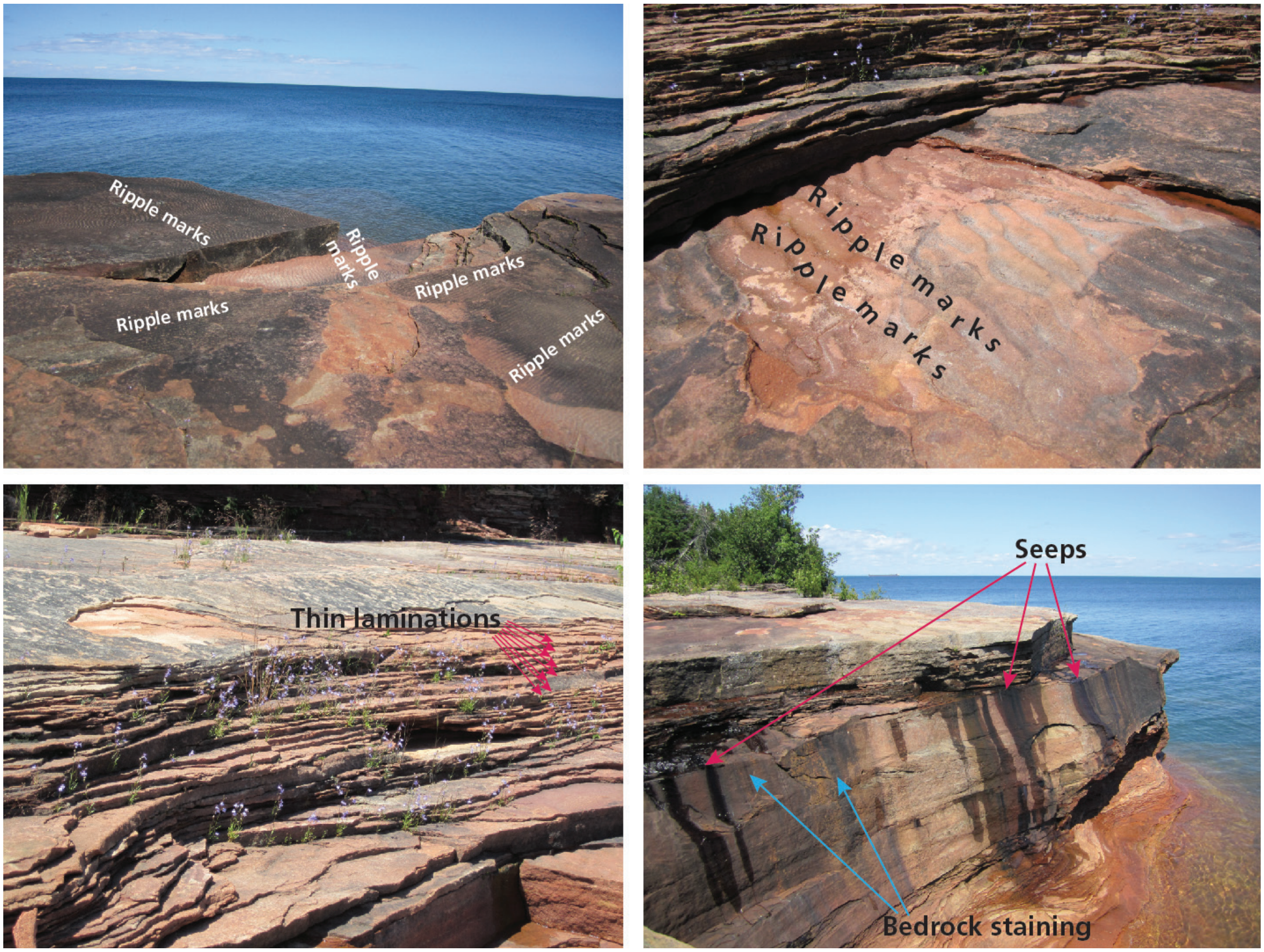


Figure 25. Bedrock features. Ripple marks are common in the layers of Devils Island Sandstone (geologic map unit PCdi) at Devils Island landing. The thin laminations typical of this unit are also visible. This thin layering lends itself to the formation of the spectacular sea caves, arches, windows, and stacks along some shorelines. Seeps flow along layers to emerge at cliff faces, causing staining of some bedrock outcrops. When the water freezes in winter, large icicles form on cliffs. Photographs by Trista L. Thornberry-Ehrlich (Colorado State University) taken in July 2010.

energy depositional environments, such as fast-moving streams, deposit larger (heavier) clasts while transporting 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. Wind also transports and deposits sand-sized or smaller clasts (table 1). Characterization of texture can aid in interpreting ancient environmental settings. Because the ancient bedrock (**PCo**, **PCdi**, and **PCch**) formed in similar (moving water) environments as the modern shoreline system (**Qc**), the saying "the present is the key to the past" (an adage summarizing uniformitarianism) is truly applicable at Apostle Islands National Lakeshore.

Sedimentary structures such as ripple marks are common in the Devils Island Sandstone (**PCdi**) (fig. 25). Providing an analogy, ripple marks can be seen forming today in the soft sands of bays such as Presque Isle or Julian Bay. Modern cross-bedding is revealed by digging into river sandbars and viewing a cross-sectional profile, while ancient cross-beds occur in the Chequamegon Sandstone (**PCch**). The mud cracks of the Chequamegon Sandstone look like mud cracks on any exposed mudflat today. Mud cracks are common in the quieter water areas such as lagoons and marshes (Cannon et al. 1999; Nuhfer and Dalles 2004).

As detailed in the Map Unit Properties Table (in pocket) and "Geologic History" section, the sandstones of

Table 1. Clastic sedimentary rock classification and characteristics.

Rock Name and Relative Energy of Depositional Environment	Clast Size	Examples at Apostle Islands
Conglomerate (rounded clasts) or Breccia (angular clasts) [higher energy]	>2 mm (0.08 in) [larger]	Isolated layers in Orienta Sandstone (PCo) and Chequamegon Sandstone (PCch)
Sandstone	1/16–2 mm (0.0025–0.08 in)	Devils Island Sandstone (PCdi)
Siltstone	1/256–1/16 mm (0.00015–0.0025 in)	None documented
Claystone [lower energy]	<1/256 mm (0.00015 in) [smaller]	Isolated shale layers in Orienta Sandstone (PCo) and Chequamegon Sandstone (PCch)

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

the Bayfield Group contain sedimentary features that indicate they were deposited in sediment-choked braided streams (**PCo** and **PCch**) and along the shorelines of shallow ponds and lakes (**PCdi**) more than a billion years ago.

Devils Island Sandstone Type Locality

Formal geologic formations take their names from geographic features such as towns, islands, and mountains that are near its type locality; that is, a place with exposures extensive enough to show all the mappable features of the formation, including the rock type, color, texture, thickness, and distinguishing features such as depositional structures (e.g., cross-beds) and the characteristic manner in which the rock weathers (e.g., forming cliffs or dissolving). Type localities are searchable at the US Geological Survey's "Geolex" database: http://ngmdb.usgs.gov/Geolex (accessed 6 April 2015).

Devils Island is the type locality for Devils Island Sandstone (**PCdi**). The type locality was first recorded by Thwaites (1912) and studied by Cannon et al. (1999) and Nuhfer and Dalles (2004) (see http://ngmdb.usgs.gov/Geolex/Units/DevilsIsland_1390.html; accessed 6 April 2015). Devils Island Sandstone and the adjacent geologic units of the Chequamegon Sandstone (**PCch**) and the Orienta Sandstone (**PCo**) compose the Bayfield Group—a formal group (composed of two or more rock formations) whose name is derived from the Bayfield Peninsula where these rocks are so well exposed (http://ngmdb.usgs.gov/Geolex/Units/Bayfield_6720.html; accessed 6 April 2015).

Douglas Fault and Other Faults

A fault is a fracture in rock along which rocks have moved. Faults are classified based on motion of rocks on either side of the fault plane (fig. 26). The three primary types of faults are normal faults, reverse faults, and strike-slip faults (fig. 26). Thrust faults are reverse faults with a low angle (less than 45°) fault plane. Thrust faults and faults of unknown offset or displacement are mapped within GRI GIS data.

The Douglas Fault is the only major, named fault included in the GRI GIS data. It cuts across the base of the Bayfield Peninsula, south of Apostle Islands National Lakeshore, and runs from the Twin Cities into northwestern Wisconsin. Along portions of its length, the fault separates the Chequamegon Sandstone (**PCch**) of the Bayfield Group from the older Freda Sandstone (**PCf**) of the Oronto Group (Cannon et al. 1999). The Douglas Fault is a reverse fault, thrusting older volcanic rocks over younger sedimentary rocks. It forms the northern margin of the St. Croix horst (fig. 27; Cannon et al. 1999; Nicholson et al. 2006). The Douglas Fault is likely a structure that originally formed as part of the Midcontinent rift and was later "reactivated" as a reverse fault. Displacement estimates approach 3,000 m (10,000 ft). Following its formation, the Douglas Fault was then offset by smaller strike-slip faults.

Aeolian 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. The NPS Geologic Resources Division Aeolian Resource Monitoring website, http://www.nature.nps.gov/geology/monitoring/aeolian.cfm (accessed 6 April 2015), provides additional information.

Aeolian features such as dunes, barriers, and sand spits (fig. 16) are described in the "Sandscapes" section.

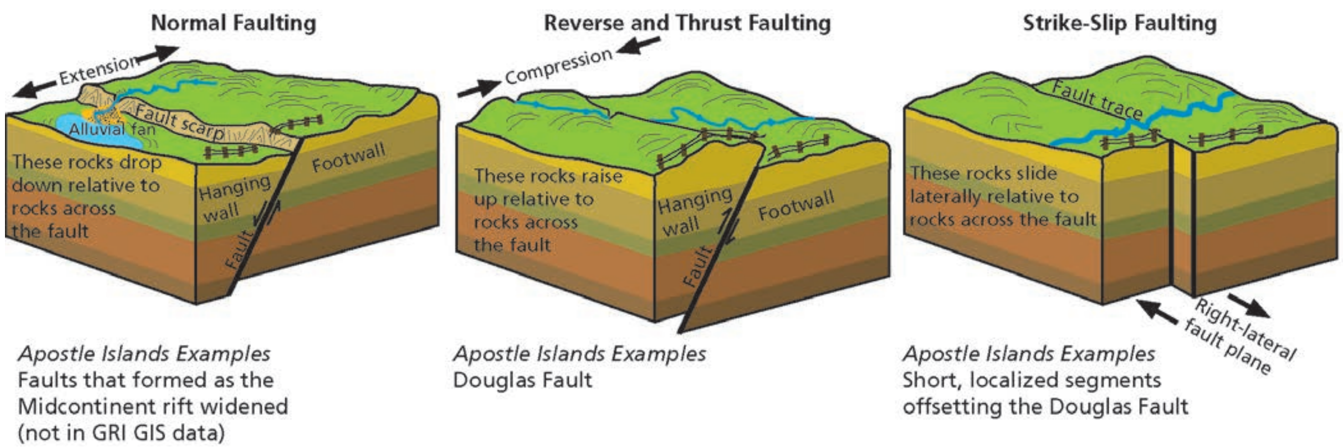


Figure 26. Schematic illustrations of fault types. Movement occurs along a fault plane. Footwalls are below the fault plane and hanging walls are above. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging wall up relative to the footwall. A thrust fault is similar to a reverse fault, but has a dip angle of less than 45°. In a strike-slip fault, the relative direction of movement of the opposing plate is lateral. When movement across the fault is to the right, it is a right-lateral (dextral) fault, as illustrated above. When movement is to the left, it is a left-lateral (sinistral) fault. A strike-slip fault between two plate boundaries is called a transform fault. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Winds scouring the surface of the glacial till banks along island shorelines contribute to their formation. Wind dries the banks causing erosion ("granular disintegration") at locations such as Michigan Island lighthouse (Julie Van Stappen and Peggy Burkman, conference call, 19 June 2014). High winds also contribute to blowdowns (areas of downed trees) that occur in broad swaths through the forest. Blowdowns cause more disturbance than fires to lakeshore forests (Thornberry-Ehrlich 2013). 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 soil development on the islands (Cary et al. 1979). Wind erosion causes the formation of blowouts which are small, saucer-shaped or trough-shaped depressions in the sand, particularly in areas where stabilizing vegetation is lacking or has been disturbed.

Loess (windblown silt) associated with glacial retreat at Apostle Islands National Lakeshore may cover some isolated areas of glacial outwash. These deposits are typically easily eroded and/or incorporated into the soil profile (Thornberry-Ehrlich 2013). They do not appear in the GRI GIS data.

Paleontological Resources

Paleontological resources (fossils) are any evidence of life preserved in a geologic context (Santucci et al. 2009). Body fossils are any remains of the actual organism such as bones, teeth, shells, or leaves. Trace fossils are evidence of biological activity; examples include burrows, tracks, or coprolites (fossil dung). Fossils in NPS areas occur in rocks or unconsolidated deposits, museum collections, and cultural contexts such as building stones or archeological resources. As of May 2015, 258 parks, including Apostle Islands National Lakeshore, had documented paleontological resources in at least one of these contexts. The NPS Geologic Resources Division Paleontology website, http://www.nature.nps.gov/geology/paleontology/index.cfm (accessed 10 April 2015), provides more information. Also see the "Paleontological Resources Inventory, Monitoring, and Protection" section of this report.

At more than 1 billion years old, the bedrock of the lakeshore is unlikely to retain body fossils. Havholm (2007) described potential trace fossils from the Devils Island Sandstone (**PCdi**). These structures appear to be bedding-parallel, sinuous burrows (Galston 2008). As of summer 2014, the status of these fossils is still unclear and a subject of ongoing research (Julie Van Stappen and Peggy Burkman, conference call, 19 June 2014). Potential microbial fossils are known from rocks of similar age in the surrounding region (Hunt et al. 2008).

As described in Hunt et al. (2008), the Apostle Islands museum collection contains six fossil specimens,

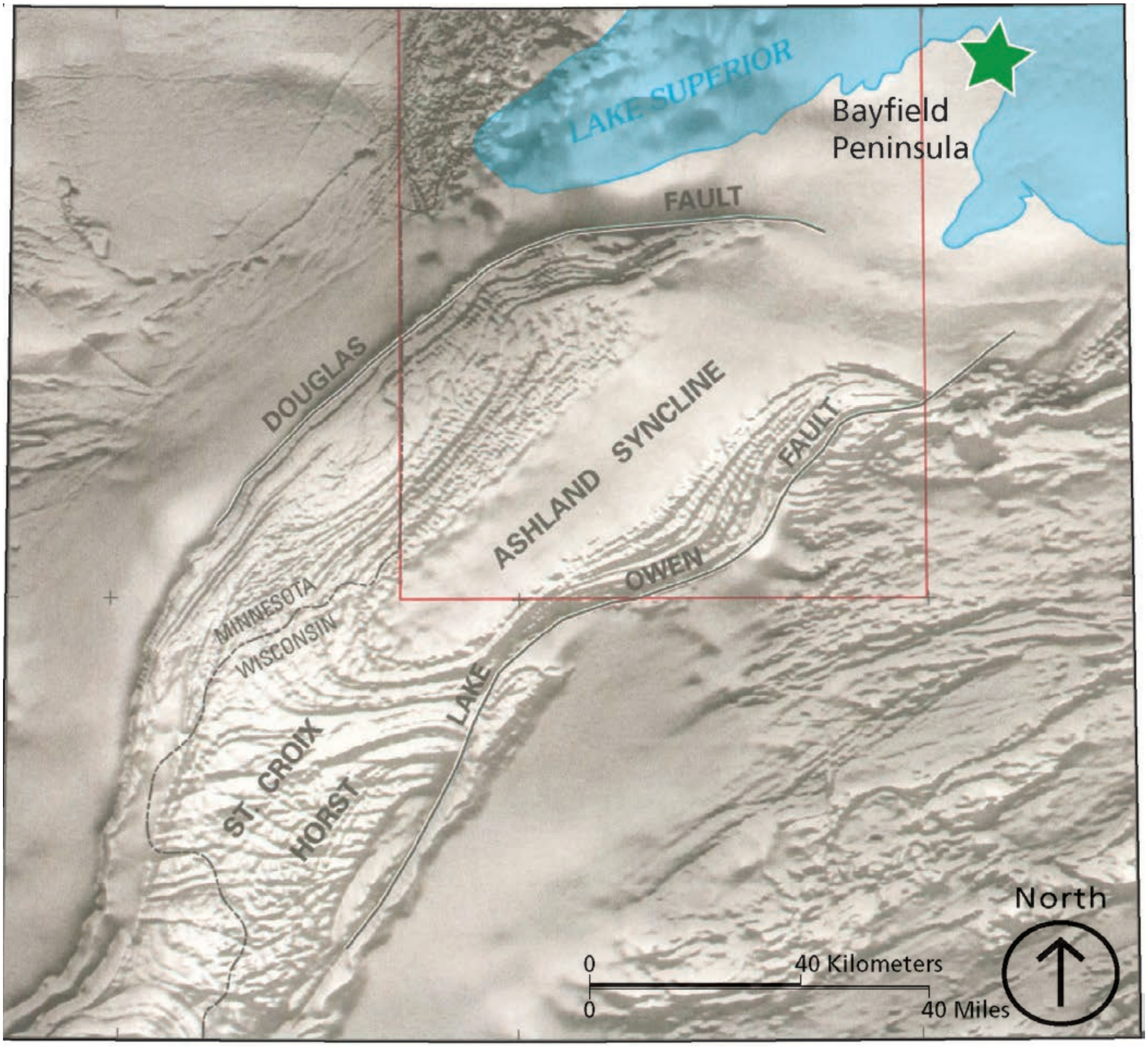


Figure 27. Aeromagnetic map showing the location of buried structures. Aeromagnetic maps display differences in Earth's magnetic field as measured from a moving aircraft along a regional grid. The maps show subsurface crustal structures because different rocks have different magnetic intensities. These structures are not visible at the surface nor do they necessarily reflect topography at the surface. Note the location of the Douglas Fault and St. Croix horst, which is a "block" of curst that moved upward along faults on either side. Adjacent blocks moved downward (relative to the St. Croix horst) along those faults. Green star is the location of Apostle Islands National Lakeshore. Red box is the area of the geologic map presented in Nicholson et al. (2006). Graphic from Nicholson et al. (2006) modified by Trista Thornberry-Ehrlich (Colorado State University).

including corals and brachiopods in chert and limestone cobbles. These were likely not in situ within but park but rather transported to the area from the north by advancing glaciers during the ice ages. Fossils also may wash onto the Lake Superior shoreline. Pleistocene or Holocene aged fossils may be discovered within the lakeshore (Hunt et al. 2008). Sediment cores from Stockton and Brander bogs, Hemlock Lake, and Lake Mary contain peat, plant and animal remains, and a pollen record as old as 9,500 years; they record vegetation and climate changes since the last major ice advance (Wilson 1935; Swain and Winkler 1983; Davis et al. 1998; Hunt et al. 2008).

Geologic Resource Management Issues

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

Apostle Islands National Lakeshore has abundant and varied shorelines and is, therefore, considered “coastal” and managed accordingly. 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 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. The coastal environment—characterized by factors such as wave energy, sediment supply, sediment type, slope and width, and past geologic history—may extend inland for many kilometers/miles (Wyckoff 1999).

During the 2010 scoping meeting (see Thornberry-Ehrlich 2013) and 2014 conference call, participants (see Appendix A) identified the following geologic resource management issues:

- Shoreline Response to Lake-Level Change
- Slope Movement Hazards and Risks
- Caves and Associated Landscape Management
- Fluvial and Other Surface Water Issues
- Abandoned Mineral Lands
- Disturbed Land Restoration
- Renewable Energy Development
- External Mineral Development
- Wind-Speed Change
- Seismic Activity Hazards and Risks
- Paleontological Resource Inventory, Monitoring, and Protection

Resource managers may find *Geological Monitoring* (Young and Norby 2009; http://go.nps.gov/geomonitoring) useful for addressing these geologic resource management issues. The manual provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. Each chapter covers a different geologic resource and includes detailed recommendations for resource managers and suggested methods of monitoring. In addition, 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 Apostle Islands National Lakeshore.

Shoreline Response to Lake-Level Change

Pendleton et al. (2007) assessed the susceptibility of the shoreline to lake-level change, creating a change-potential index (CPI) for Apostle Islands National Lakeshore (fig. 28). This CPI used geomorphology, shoreline change potential (m/year), coastal slope (%), historical rate of relative lake-level change (mm/year), annual ice cover (days), and wave height (m) to create a relative measure of the coastal system’s vulnerability to the effects of lake-level change. Areas where the physical effects of coastal and lake-level change might be greatest are highlighted. The CPI provides data for resource management and lakeshores facilities plans. For more information about CPIs and the coastal-vulnerability index (CVI), refer to the US Geological Survey CVI website: http://woodshole.er.usgs.gov/project-pages/nps-cvi/.

The nearly 257 km (160 mi) of shorelines in Apostle Islands National Lakeshore consist of sand and gravel beaches (**Qc**), rock outcrops (**PCdi**, **PCch**, and **PCo**), and dune and glacial bluffs (**Qgl** and **Qgw**). The shoreline geomorphology is a function of the type of geologic foundation (i.e., rock type) present as well as its position relative to the wave energy of Lake Superior (i.e., on the lee side or facing direct wave energy). Rocky, cliff-lined coasts have the lowest coastal change potential whereas sandy beaches and mudflat areas have the highest (Pendleton et al. 2007). Overall, 21% of the mapped shoreline was classified as having a very high change potential, 30% as high, 25% as moderate, and 24% as low change potential due to future lake-level change (Pendleton et al. 2007).

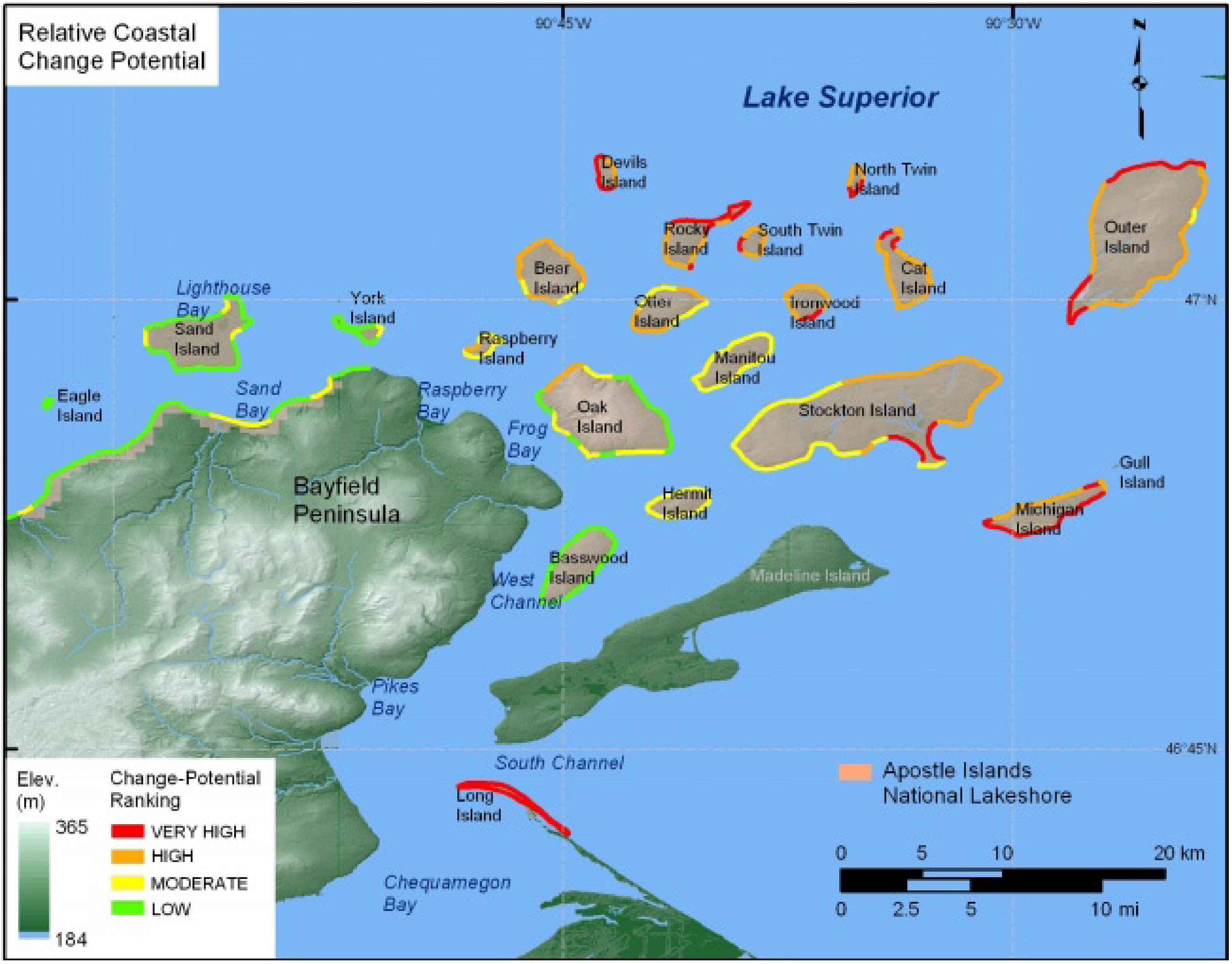


Figure 28. Relative coastal-change potential for Apostle Islands National Lakeshore. Investigators determined the relative change potential index (CPI) of shorelines at Apostle Islands National Lakeshore based on six variables: geomorphology, regional coastal slope, rate and direction (i.e., rise and fall) of relative lake-level change, historical shoreline change rates, annual ice cover and mean significant wave height. The colored shorelines on the graphic represent these rankings from low (green) to very high (red). The highest change-potential shorelines are along sandy stretches with significant wave heights. The lowest change-potential shorelines are bluffs and cliffs where wave heights are lower. Graphic from Pendleton et al. (2007, figure 13A) available at http://pubs.usgs.gov/of/2005/1249/html/fig13a.html (accessed 19 June 2014).

Engstrom (1985) noted that if lake levels rose, beaches on the inner islands and spits (**Qc**) would decrease due to a limited sand supply. Declining lake levels are locally associated with progradation of sand features, building outward into the lake (fig. 29). Glacial till (**Qgl** and **Qgw**) is a local source of sand (and other sediment) nourishment. Islands with thick glacial till cover, such as Outer, Michigan, Rocky, Cat, and South Twin, have a local supply of sand and would be less affected. Islands lacking a thick glacial till cover, such as Devils, North Twin, Eagle, and Gull would experience more loss of depositional features (Engstrom 1985; Nuhfer and Dalles 2004).

In the recent past, lake levels have changed profoundly 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 have dropped to near 1930s Dust Bowl conditions. In 2007, the lake was 56 cm (22 in) below normal (Climate Change Response Program 2012). As described in the “Lake Superior Shoreline” section, the winter of 2013–2014 caused a lake-level

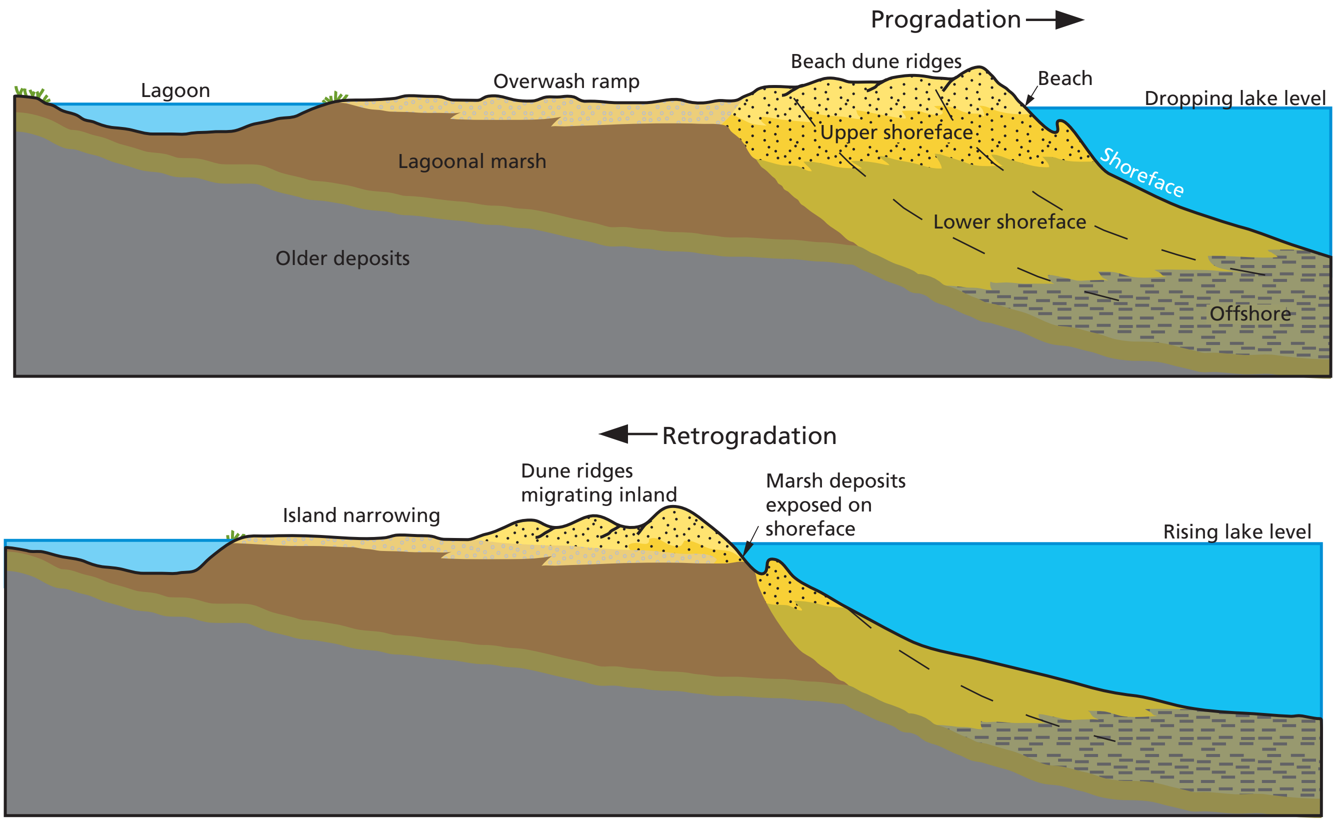


Figure 29. Prograding and retrograding barrier features. The location and morphology of larger sand features such as Long Island and the double tombolo connecting Stockton Island and Presque Isle will be affected by progradation (building outward into the lake) and retrogradation (landward stepping of the shoreline) as a result of changing lake levels. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) based on an unpublished figure provided by Kathleen Farrell (North Carolina Geological Survey) in 2010.

spike and in turn, accelerated shoreline erosion and change. Due to higher lake levels, beaches throughout the lakeshore were greatly reduced and a considerable amount of erosion occurred, as well as changes to sand spits. Near the Outer Island sand spit campsite, as much as 3 to 5 m (10 to 15 ft) eroded, and the tip of the sand spit was breached (Julie Van Stappen, chief of Resource Management, Apostle Islands National Lakeshore, written communication, 9 January 2015). The riprap stabilizing the northern end of Outer Island (below the lighthouse) used to be fronted by a large beach. In spring 2014, the beach disappeared due to high lake levels and wave action (Julie Van Stappen and Peggy Burkman, Apostle Islands National Lakeshore, chief of Resource Management and biologist, conference call, 19 June 2014).

Lake levels and shoreline changes are controlled by myriad factors such as isostatic rebound (commonly in response to removal of continental glaciers present during ice ages), 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). At Outer Island, this rise was measured at 3 mm/year (0.1 in/year) (Gable and Hatton 1983; Nuhfer and Dalles 2004). Potentially this tilt will cause southern shorelines to recede and lake level to rise; however, other factors, such as climate change, will have impacts.

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 (5.4°F) by 2100 (Pendleton et al. 2007; Great Lakes Network 2007, 2009; Melillo et al. 2014). A warmer, drier climate will result in more evaporation, less recharge, and ultimately lower lake levels and warmer water. Since

2002, warmer temperatures and lower precipitation have led to drought-like conditions (Great Lakes Network 2013). Despite recent exceptions to the trend (e.g., the cold winter of 2013–2014), the winter ice cover will also decrease in area and duration. 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. Data from climate models suggest 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). Modeling by Caffrey (2007) suggested decreases in lake levels would eventually join Sand Island with the Bayfield Peninsula. Much of the southern Chequamegon Bay would also be exposed.

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 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).

Monitoring and Research of Lake-Level Change

Resource management specialists at the National Park Service are examining and considering the National Oceanographic and Atmospheric Administration's (NOAA) National Ocean Service's 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 Apostle Islands National Lakeshore (Lynda Bell, written communication, 21 January 2015).

Management of Shoreline Change

In order to protect natural and cultural resources located on the shorelines of Apostle Islands National Lakeshore, at least eight coastal engineering projects were undertaken. Bank and slope stabilization occurred at Raspberry Island to protect the lighthouse there. Stone revetments and slope stabilization occurred on Outer Island. Revetments were also constructed at Little Sand Bay Harbor on the Bayfield Peninsula (Coburn et al. 2010). No beach nourishment occurs with the lakeshore. Some dredging for local road work occurs at the Little Sand Bay marina and at Stockton Presque Isle Harbor (Thornberry-Ehrlich 2013).

The sandscapes within the lakeshore are very dynamic and heavily used. Understanding the details of how sand is moving around and between the islands and the mainland is a resource management need (Julie Van Stappen and Peggy Burkman, conference call, 19 June 2014). Repeat aerial photography, GIS analysis, and detailed surficial geologic mapping would help in coastal-processes and shoreline-change models, and would refine the lake level-change history. This need was identified in 2010; discussions with the Wisconsin Geological and Natural History Survey to complete mapping are ongoing (Thornberry-Ehrlich 2013). The Great Lakes Network uses satellite imagery to monitor landscape dynamics in the Apostle Islands; analysis of disturbances occurs every six years as part of the Land Cover and Land Use program (Gafvert 2009; Great Lakes Network 2012b).

Geospatial data layers available for the lakeshore include national land cover data, coarse-scale Landsat from 1984–present, color infrared (CIR) imagery, recent aerial photographs, high-resolution satellite imagery, early historical imagery, and light detection and ranging (LiDAR) from the US Army Corps of Engineers (Gafvert 2009). Such data could also be used in sandscape monitoring. As discussed in the "Sandscapes" section, Engstrom (1974a, 1974b) used quantitative measurements of wave statistics, wave characteristics, and shore morphology to create a model of foreshore sedimentology and morphology.

Because shorelines are so 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 lake 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.

Recognizing that climate is a primary driver of most biological and physical processes in natural ecosystems, the Great Lakes Network monitors land-cover and land-use disturbances, water quality, vegetation, persistent contaminants, phenology, and weather and climate to understand how climate change is affecting the entire ecosystem (Great Lakes Network 2009, 2012a). In 2007, low lake levels required short- and long-term responses to ensure visitor access to facilities such as docks. 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 general-management planning and include monitoring and assessing predicted and actual impacts of climate change (National Park Service 2011).

Multidisciplinary and multi-resource assessments are ongoing research needs at the lakeshore, although limited resources exist. Michigan Technological University and other groups are currently assessing climate change vulnerability of park resources. 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.

Slope Movement Hazards and Risks

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

As described in the “Slope Movements” section, slope processes occur on the landscape at Apostle Islands National Lakeshore. These processes are natural elements of shoreline evolution. For example, along the Wisconsin Lake Superior shoreline, 85% of glacial till bluffs (**Qgh**, **Qgl**, **Qgw**, and **Qou**) were identified as unstable (Clayton 1985; Anderson 2003). This situation is likely comparable to that at the Apostle Islands. Some slope processes could threaten cultural resources and/or visitor safety at the lakeshore.

At Raspberry and Outer islands, shoreline stabilization techniques were implemented to protect historic lighthouses. At Raspberry Island, riprap (gabbro boulders), slope reduction, vegetation, log cribs, facines, brush layering, and drainage systems were installed to slow shoreline erosion (see “Management of Shoreline Change” section). The importation of soil unfortunately introduced exotic species, which required further resource management action. On Outer Island, riprap, drainage trenches, and bioengineering combined to maintain a more stable, natural looking slope (fig. 30; Thornberry-Ehrlich 2013). As described in the “Shoreline Response to Lake-Level Change” section, higher lake levels have since removed a large beach that was lakeward of the riprap installed on the northern end of Outer Island (Julie Van Stappen and Peggy Burkman, conference call, 19 June 2014).

Rockfall occurs in the lakeshore on the islands rimmed by sandstone cliffs (**PCdi**, **PCch**, and **PCo**), although the parkwide frequency and magnitude of rockfall is not known quantitatively. Falling material ranges in size from pebbles and rocks to larger blocks and, in the case of Oak Island in 2010, an entire sea arch. The intersections of joints and fractures create weak areas susceptible to rockfall. Wave erosion and frost weathering—whereby water expands upon freezing, and the resulting ice wedges rocks apart along cracks and fractures—contribute to the instability of the cliffs. These natural processes become hazards when kayakers

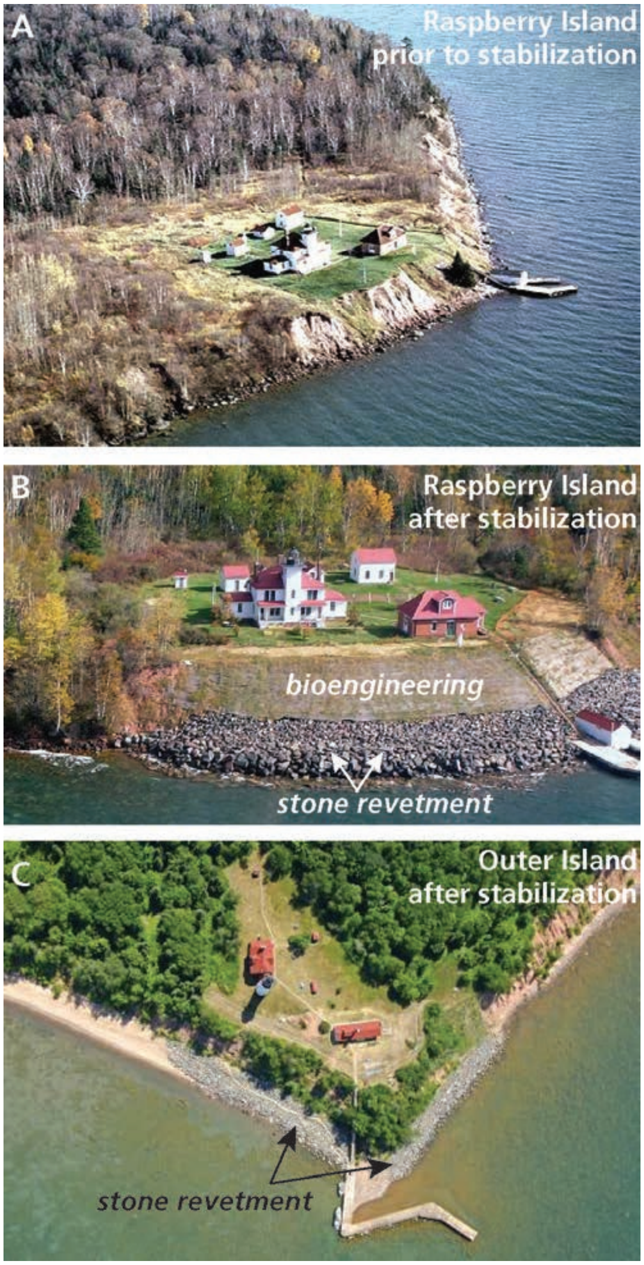


Figure 30. Coastal stabilization sites at Apostle Islands National Lakeshore. (A) shows Raspberry Island shoreline before stabilization, and (B) shows the shoreline below the lighthouse after stabilization. (C) shows riprap installed at the base of the slope below the lighthouse at Outer Island. Photographs from Coburn et al. (2010; figures 3, 6, and 7, respectively).

or visitors hiking on winter ice travel near the base of the cliffs or in sea caves (see "Caves and Associated Landscape Management" section).

Particularly hazardous areas are those with visible cracks, loose material, or overhangs. Alerting visitors to the hazards associated with rockfall near the base of cliffs or in sea caves is a first step toward reducing the risk. Such information could be presented via the park website, brochures, signage, and/or verbal communication from park staff.

If funding permits, resource managers could consider obtaining quantitative information to assess the frequency and magnitude of rockfall (and other slope movements) in high visitation areas. A photomonitoring program is one possibility. The Geoscientist-in-the-Parks program (http://www.nature.nps.gov/geology/gip/index.cfm; accessed 3 April 2015) is an option to support such a project. The NPS Geologic Resources Division Photogrammetry website (http://www.nature.nps.gov/geology/monitoring/photogrammetry/index.cfm) provides examples of how photographic techniques support structural analysis of rockfall areas.

The following references provide additional background information, suggested vital signs, and resources for assessing and documenting slope movements: Wieczorek and Snyder (2009), Highland and Bobrowsky (2008), the US Geological Survey landslides website (http://landslides.usgs.gov/), the NPS Geologic Resources Division Geohazards (http://www.nature.nps.gov/geology/hazards/index.cfm) and Slope Movement Monitoring (http://www.nature.nps.gov/geology/monitoring/slopes.cfm) websites. 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 landslide, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessment of landslide hazards and risks.

Caves and Associated Landscape Management

Cave features are non-renewable 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 also Appendix B).

A park-specific cave management plan has not yet been completed for Apostle Islands National Lakeshore. 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. Rockfall within and near caves is a potential visitor safety concern particularly during the winter when visitation increases dramatically (see "Slope Movement Hazards and Risks" section). A cave management plan would also address issues associated with ephemeral but very popular ice caves. Cave management plans also propose ways to survey and study known caves and discover new ones. The NPS Geologic Resources Division can facilitate the development of a cave management plan.

The sea caves at the lakeshore provide some limited bat habitat. Scientists from the Department of Natural Resources surveyed for bat habitat and found several areas. The extent is limited by the exposed nature of the sea caves. Resource managers are interested in a summer survey (Ulf Gafvert, Julie Van Stappen, and Peggy Burkman, conference call, 19 June 2014).

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; (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.

Fluvial and Other Surface Water Issues

The fluvial features at Apostle Islands National Lakeshore are largely ephemeral in nature. As described in the "Fluvial Features" section, the Sand River is the primary fluvial resource within the park. As this river meanders across its floodplain within the unconsolidated glacial till deposits (**Qgw** and **Qgl**) and its own postglacial stream sediment (**Qsm**), slumping and undercutting are occurring.

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.

Several open-water lagoons are associated with sandscapes on the Apostle Islands. Some of these are acidic and lack the ability to buffer acid deposition from precipitation. High levels of methyl mercury have been recorded in the Outer and Stockton islands' lagoons (Rolfhus et al. 2005). The Great Lakes Network currently monitors water quality in the coastal wetlands and open-water lagoons on Outer, Stockton, and Michigan islands, and at the mainland's Little Sandy Bay (Great Lakes Network 2011b). Detailed water quality discussions are beyond the scope of this report. The NPS Water Resources Division can provide more information and assistance (see http://www.nature.nps.gov/water/; accessed 6 April 2015).

Abandoned Mineral Lands

According to the NPS Abandoned Mineral Lands (AML) database (accessed 3 June 2014) and Burghardt et al. (2014), Apostle Islands National Lakeshore contains four AML features at four sites: Breckenridge Quarry and Bass Island Brownstone (Basswood Island), Ashland Brownstone Company (Stockton Island), and Excelsior Brownstone Quarry (Hermit Island). Features include waste rock piles and a well into the Chequamegon Sandstone (**PCch**). Servicewide, AML features present a variety of resource management issues for visitor and staff safety; air, water, and soil quality; as well as providing habitat for animals. Resource management of AML features requires an accurate inventory and reporting. All AML features should be recorded in the AML database (the NPS Geologic Resources Division may be able to provide assistance). An accurate inventory can identify human safety hazards, and facilitate reclamation and restoration of features. When appropriate for resource

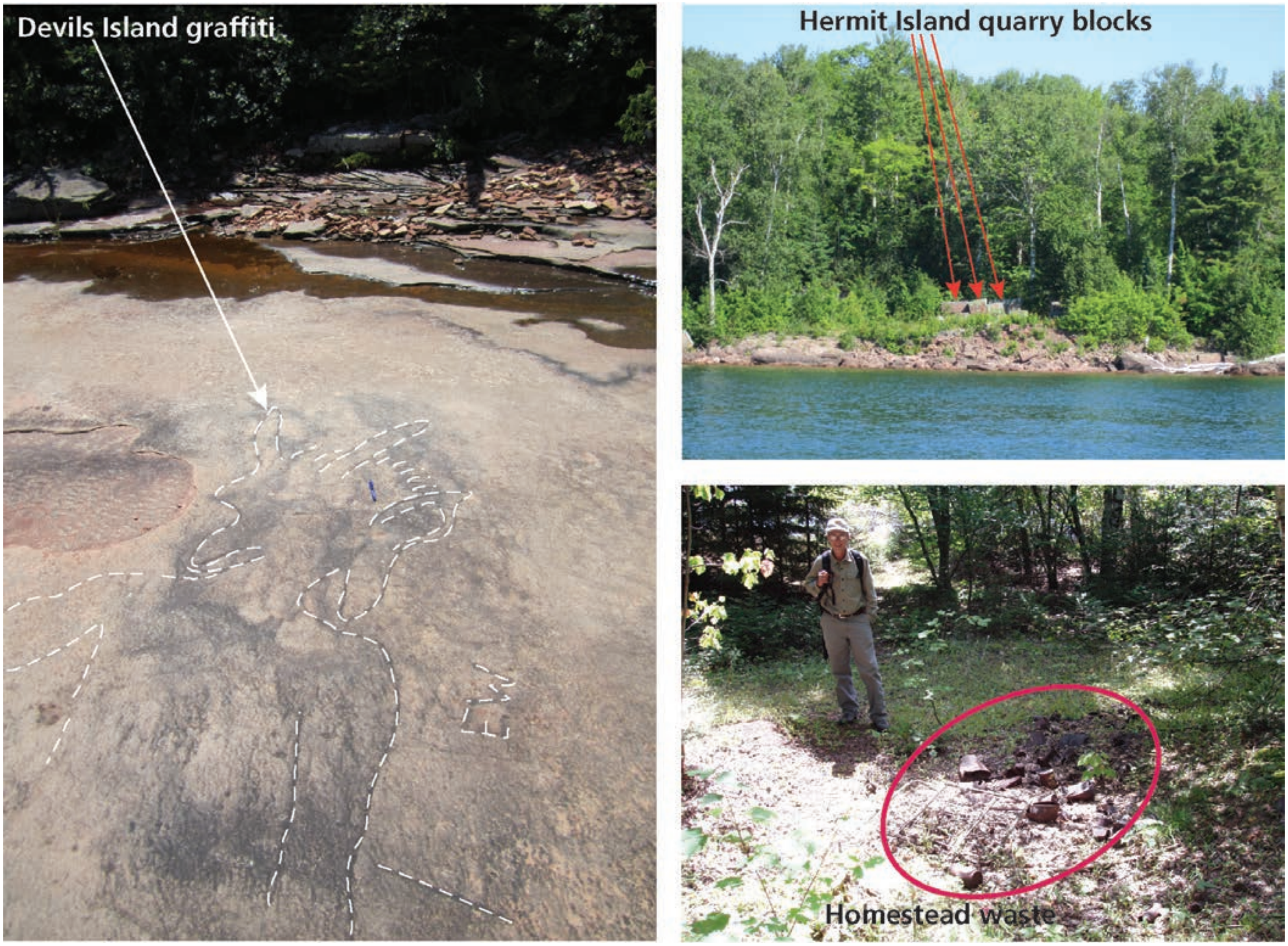


Figure 31. Disturbed lands at Apostle Islands National Lakeshore. Bedrock outcrops are occasionally vandalized with graffiti or removal of material. The quarry on Hermit Island still contains cut Chequamegon Sandstone (geologic map unit PCch) blocks. These blocks were ready for transport but left in place, and are now interpretive targets. Old homesteads are being naturally reclaimed in the forests on some islands such as Ironwood Island. Photographs by Trista L. Thornberry-Ehrlich (Colorado State University; left and upper right) taken in July 2010; and Hal Pranger (NPS Geologic Resources Division; bottom right) taken in August 2005.

management and visitor safety, features can also present opportunities for interpretation as cultural resources. Access to two AML features within the lakeshore has already been restricted with wooden fences and railings. The two other listed features are not ranked for mitigation priority (Burghardt et al. 2014). The NPS AML Program website, http://nature.nps.gov/geology/aml/index.cfm, provides further information.

Disturbed Land Restoration

Apostle Islands National Lakeshore has a long history of human use. As detailed in the "Geologic Significance and Connections" section, land use ranged from homesteads, sandstone quarries, and fishing villages to lighthouses and landings. Many of the "disturbed" lands within the lakeshore are now considered cultural resources and are interpreted with signs and exhibits (Julie Van Stappen and Peggy Burkman, conference call, 19 June 2014; Burghardt et al. 2014). For example, bedrock quarries are now interpretive targets and vegetation is cleared to maintain the cultural resource (Thornberry-Ehrlich 2013). Structures without cultural significance mostly are being allowed to reach a state of equilibrium with the natural environment (fig. 31; Thornberry-Ehrlich 2013). Extensive logging took place between the mid-1800s and 1940 with some sporadic logging occurring as recently as 1974. Forests are recovering, but with targeted species in lower abundance than historically.

Coastal beaches and dune areas are particularly vulnerable to degradation from disturbances caused by past logging, heavy visitor use, and exotic vegetation. 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 impacts have been caused by current and/or past human activities. Restoration work has occurred on Ironwood, Long, Oak, Raspberry, South Twin, and Stockton islands, and on a number of sandscapes (Julie Van Stappen, written communication, 9 January 2015).

Park resource managers are uncertain how much upland soil erosion resulted from logging activities (Thornberry-Ehrlich 2013). Comparison of the composition of diatoms (siliceous algae) in lake-sediment cores reveals a significant shift in water quality as a result of farming and logging around the time of Euro-American settlement. Changes could be due to increased sedimentation. Monitoring modern diatom community composition and comparing it to historical variations are providing a means of understanding the nature of water quality changes in Lake Superior and whether changes are due to climate change, land use, or natural factors (Great Lakes Network 2011a).

Renewable Energy Development

Generation and transmission of renewable energy includes utility-scale solar, wind, geothermal, off-shore wind technologies, and hydroelectricity. The National Park Service uses a combined technical and policy approach to manage and protect park resources and values as renewable energy resources are identified and developed near NPS areas. Park resources and values that may be impacted by renewable energy development include water quantity and quality, air quality, wildlife, dark night skies, natural soundscapes, cultural resources, scenic views, soils, geologic and hydrologic processes, and visitor experience. The NPS Geologic Resources Division Renewable Energy website, http://nature.nps.gov/geology/energy/index.cfm, provides more information.

Proposals were being circulated in 2010 to develop wind farms on Madeline Island and the mainland. Development would have significant impacts to the lakeshore's viewshed and temporarily increase local traffic during the construction period (Thornberry-Ehrlich 2013). Since that time, no new proposals have been made and no renewable energy development has occurred (Julie Van Stappen and Peggy Burkman, conference call, 19 June 2014).

External Mineral Development

The National Park Service works with adjacent land managers and other permitting entities to help ensure that National Park System resources and values are not adversely impacted by external mineral exploration and development. Potential impacts include groundwater and surface water contamination, erosion and siltation, introduction of exotic plant species, reduction of wildlife habitat, impairment of viewsheds and night skies, excessive noise, and diminished air quality. Visitor safety and overall degradation of the visitor experience are particular concerns.

As of June 2014, a large iron mine is being proposed for an area 50 km (30 mi) south of Apostle Islands National Lakeshore (Laurel Woodruff, US Geological Survey, geologist, conference call, 19 June 2014). Preliminary drilling for an economic assessment of the Gogebic Iron Range of Wisconsin is underway. The Gogebic Iron Range includes Proterozoic strata of the Keweenawan Supergroup and, prior to the 1960s, was one of the Lake Superior region's major iron-producing districts (Cannon et al. 1999). A possible outcome is a large, open-pit mine. An operation of this scale would introduce significant impacts to the lakeshore area including increased traffic, air pollution, and noise. The most important potential impact is related to water quality from streams such as Bad River flowing from the mine area to the lakeshore. In order to anticipate potential impacts, factors such as water flow, sedimentation, and currents should be incorporated into modeling (Laurel Woodruff, Ulf Gafvert, Julie Van Stappen, and Peggy Burkman, conference call, 19 June 2014).

Miller (date unknown) detailed the mineral occurrences within and adjacent to the lakeshore, including early efforts to search for oil and gas. The NPS Geologic Resources Division is available to provide lakeshore managers with policy and technical assistance regarding minerals and energy issues. Recommendations include remaining aware of public and private mineral ownership and speculation, exploration, or drilling activity on lands in the vicinity of the lakeshore. Regulations and permit procedures vary among states. The NPS Geologic Resources

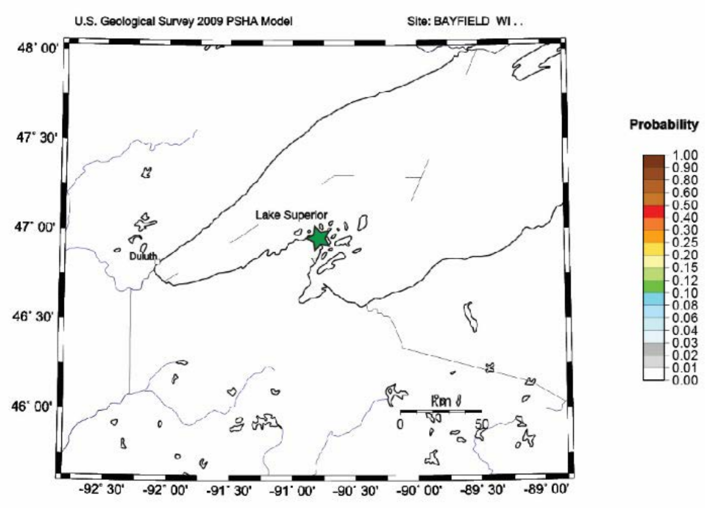


Figure 32. Probability of earthquakes with magnitude greater than 5.0. This probability assumes a 100-year timespan and a 50-km (30-mi) radius around Apostle Islands National Lakeshore (green star). The very low probability does not rule out smaller earthquakes or the chance that a larger earthquake may occur. Graphic generated using the US Geological Survey earthquake probability mapping program (https://geohazards.usgs.gov/eqprob/2009/index.php; accessed 1 August 2014).

Division Energy and Minerals website, http://nature.nps.gov/geology/minerals/index.cfm, provides additional information.

Wind-Speed Change

Blowing wind is one of the agents of landform change at Apostle Islands National Lakeshore (see "Aeolian Processes" section). Local wind speeds are increasing at rates approaching 5% per decade (Desai et al. 2009). This is likely related to climate change (Desai et al. 2009; Julie Van Stappen and Peggy Burkman, conference call, 19 June 2014; see "Shoreline Response to Lake-Level Change" section). Increasing temperatures of air and surface water, decreases in winter ice, and a reduction in the temperature gradient between air and water are 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 bluffs, increase tree blowdowns, and promote the formation of aeolian features in sandscapes.

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. Monitoring aeolian features and processes may aid in predicting the impacts of changing wind speeds on the landforms at the lakeshore.

Seismic Activity Hazards and Risks

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.

Apostle Islands National Lakeshore is not located near an active seismic zone. The US Geological Survey's earthquake probability maps (http://geohazards.usgs.gov/eqprob/2009/, accessed 1 August April 2014) indicate an almost 0% probability of a magnitude-5.0 (moderate) or greater earthquake occurring in the next 100 years at Apostle Islands National Lakeshore (fig. 32; Peterson et al. 2008). Since melting of the last ice age continental glaciers, isostatic rebound of the land surface may cause small earthquakes to occur occasionally at the lakeshore as the crust adjusts to the lack of weight of the ice; however, most of these events range in magnitude between 2 and 3 and are too minor to be felt by humans (Thornberry-Ehrlich 2013).

If resource management staff members are interested in seismic potential or activity in the area, the multidisciplinary Earthscope program is serving seismic data to measure motions of Earth's surface (see http://www.earthscope.org; accessed 6 April 2015). This program has magnetotelluric stations and seismometers in the Bayfield area. The NPS Geologic Resources

Division Seismic Monitoring website (http://nature.nps.gov/geology/monitoring/seismic.cfm; accessed 6 April 2015) and the US Geological Survey Earthquakes Hazards website (http://earthquake.usgs.gov/; accessed 6 April 2015) provide additional information.

Paleontological Resource Inventory, Monitoring, and Protection

As discussed in the "Paleontological Resources" section, Apostle Islands National Lakeshore contains possible ancient trace fossils and fossils in glacial deposits, and has the potential for younger fossils. All paleontological resources are non-renewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act (see Appendix B). As of May 2015, Department of Interior regulations associated with the act were still under development.

A field-based paleontological resource survey has not been completed for Apostle Islands National Lakeshore but could provide detailed, site-specific descriptions and resource management recommendations. Hunt et al. (2008) suggested development of a paleontological resource management plan including in situ fossils and those that may potentially wash onto the shoreline at the national lakeshore and become subjected to "beachcombing." 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. Brunner et al. (2009) discussed policy and resource management considerations associated with NPS fossils along coastlines.

Geologic History

This section describes the chronology of geologic events that formed the present landscape of Apostle Islands National Lakeshore.

2.5 Billion to 1.6 Billion Years Ago (Archean Eon and Paleoproterozoic Era)—North American Craton Forms

Wisconsin contains some of the oldest rocks in North America. Before 2.5 billion years ago, granitic crust formed and was metamorphosed in a series of events that related to the formation of the North American craton—the old, stable, core of the continent (fig. 33A). Periodic mountain-building orogenies, uplift, erosion, and volcanism occurred from about 1.8 billion to 1.6 billion years ago (Nuhfer and Dalles 2004). These rocks ("**W**" geologic map units shown only in cross sections) are now buried deep beneath the Apostle Islands (see fig. 5), but their presence impacted the deposition of the rocks exposed in the lakeshore. Mesoproterozoic (1.6 billion–1.0 billion years ago) sedimentary units thicken away from White's Ridge, one such structure comprised of "**W**" rocks. More than 2.5 billion years ago White's Ridge was a regional highpoint. The Freda Sandstone (**PCf**)—which is on the geologic map for Apostle Islands National Lakeshore but not mapped within the boundaries—is the oldest geologic unit draped over the ancient ridge (Cannon et al. 1999).

1.6 Billion to 1.0 Billion Years Ago (Mesoproterozoic Era)—Continental Rifting, Volcanism, and Sandstone Deposition

Approximately 1.1 billion years ago, the craton of the North American continent began to split in response to a rising mantle plume or body of molten rock. In a setting analogous to today's East African rift, the Midcontinent rift formed in several stages as the crust thinned over tens of millions of years from about 1.1 billion (figs. 34A and 33B) to 1.05 billion years ago (Hinze et al. 1997; Ojakangas et al. 1997). At this time, the proto–North American landmass called "Laurentia" was part of the supercontinent Rodinia, which included most continental crust in existence at the time.

Initial rifting involved fracturing of Earth's crust, which led to eruptions of lava and intrusions of molten material (plutons) along the rift. Lava flowed from vents along the center of the rift, which spread laterally. The earliest lavas to erupt (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 (figs. 34B and 34C; Hinze et al. 1997; Cannon et al. 1999). The Portage Lake Volcanics, famous for their native copper deposits, were flood basalts erupted rapidly between 1.096 billion and 1.094 billion years ago (fig. 34D; Davis and Paces 1990; Cannon et al. 1999). Those copper deposits would eventually drive centuries of copper mining and associated industry as interpreted at Keweenaw National Historical Park in Michigan. During periods of volcanic quiescence, conglomerate and sandstone were deposited. Collectively, the 30-km (19-mi) thick accumulated volcanic, plutonic, and sedimentary rocks compose the Keweenawan Supergroup (Behrendt et al. 1988; Cannon et al. 1999; Thornberry-Ehrlich 2013; Richard Ojakangas, University of Minnesota Duluth, geologist, written communication, 12 January 2015).

Downward movement along normal faults associated with the rift created a major graben (basin) in the Lake Superior region. Following the eruption of the Lake Shore Traps approximately 1.086 billion years ago, volcanism ceased during the next phase of the rift development (Cannon and Nicholson 1992; Ojakangas et al. 1997; Cannon et al. 1999). Volcanic rocks on the flanks of the rift were eroded, supplying sediments that would be deposited as conglomerate and sandstone of the Oronto Group, including the Freda Sandstone (**PCf**), which is the youngest formation of the group (fig. 34E; Cannon et al. 1999; Nuhfer and Dalles 2004; Ojakangas et al. 2011).

Older, granitic rock on the rift flanks supplied sediment to the basin as it continued to subside. Streams carried sediments northward and eastward from the high relief flanks (fig. 35). These younger sediments of the Bayfield Group buried the older rocks of the Oronto Group. The Bayfield Group, which is exposed at Apostle Islands National Lakeshore, comprises the Orienta Sandstone (**PCo**), the Devils Island Sandstone (**PCdi**) and the Chequamegon Sandstone (**PCch**); it was deposited approximately 1.0 billion years ago (Cannon et al. 1999; Nuhfer and Dalles 2004).

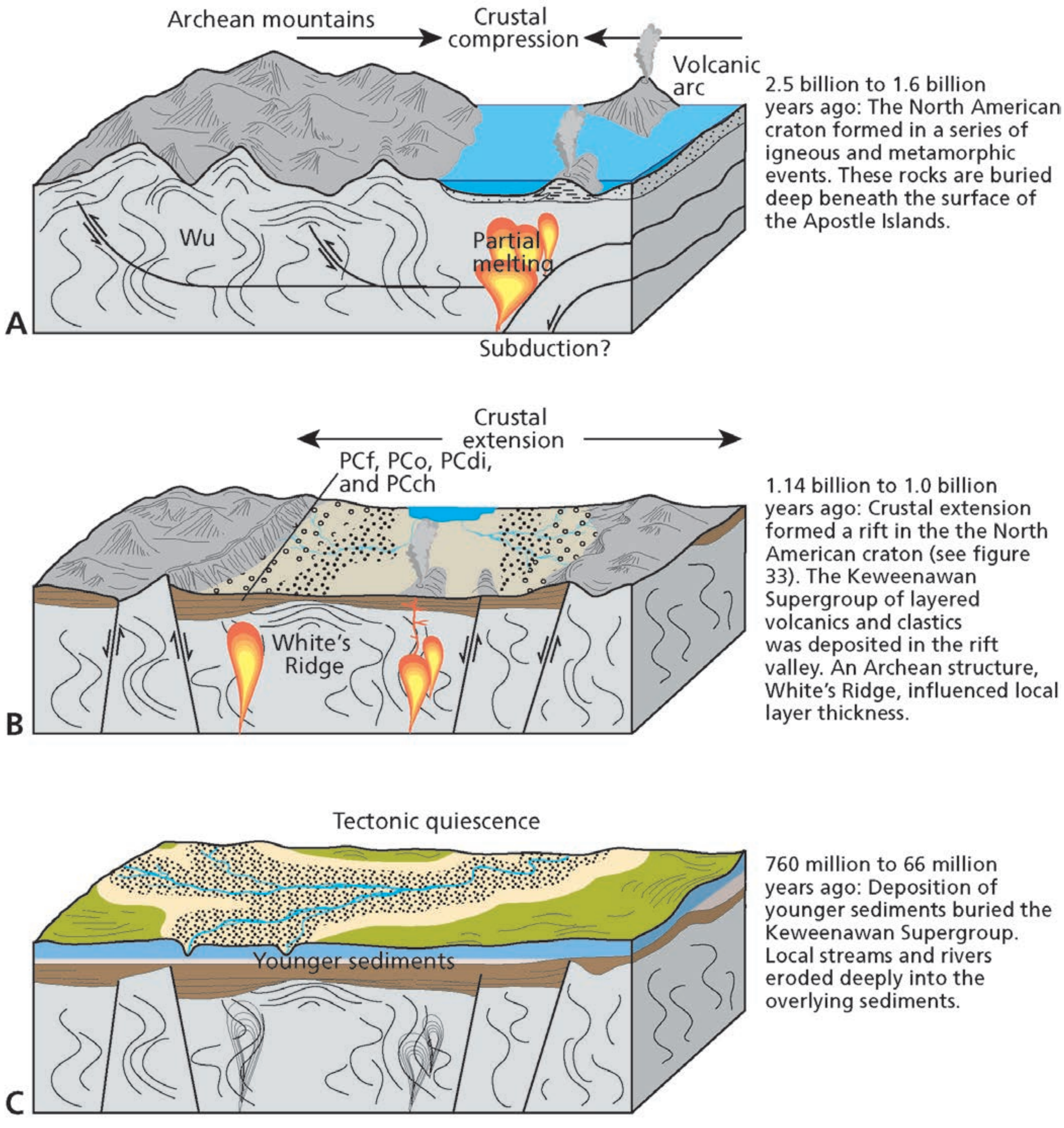


Figure 33 A–C. Schematic graphics illustrating the evolution of the landscape and geologic foundation of Apostle Islands National Lakeshore. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using information from Ojakangas et al. (2011), Nuhfer and Dalles (2004), Clayton (1984), and Cannon et al. (1999).

The Orienta Sandstone (**PCo**) is an arkose (feldspar-rich sandstone) derived, in this case, from weathered granites (Culler and Berendsen 1988; Nuhfer and Dalles 2004). The mineral feldspar tends to break down faster than quartz, so as sediments containing these minerals are transported, weathered, and worked by wind and water, the feldspar component gradually diminishes with respect to the quartz component. Feldspar-rich sediment typically accumulated relatively close to its source rock. Sedimentary features such as ripples and

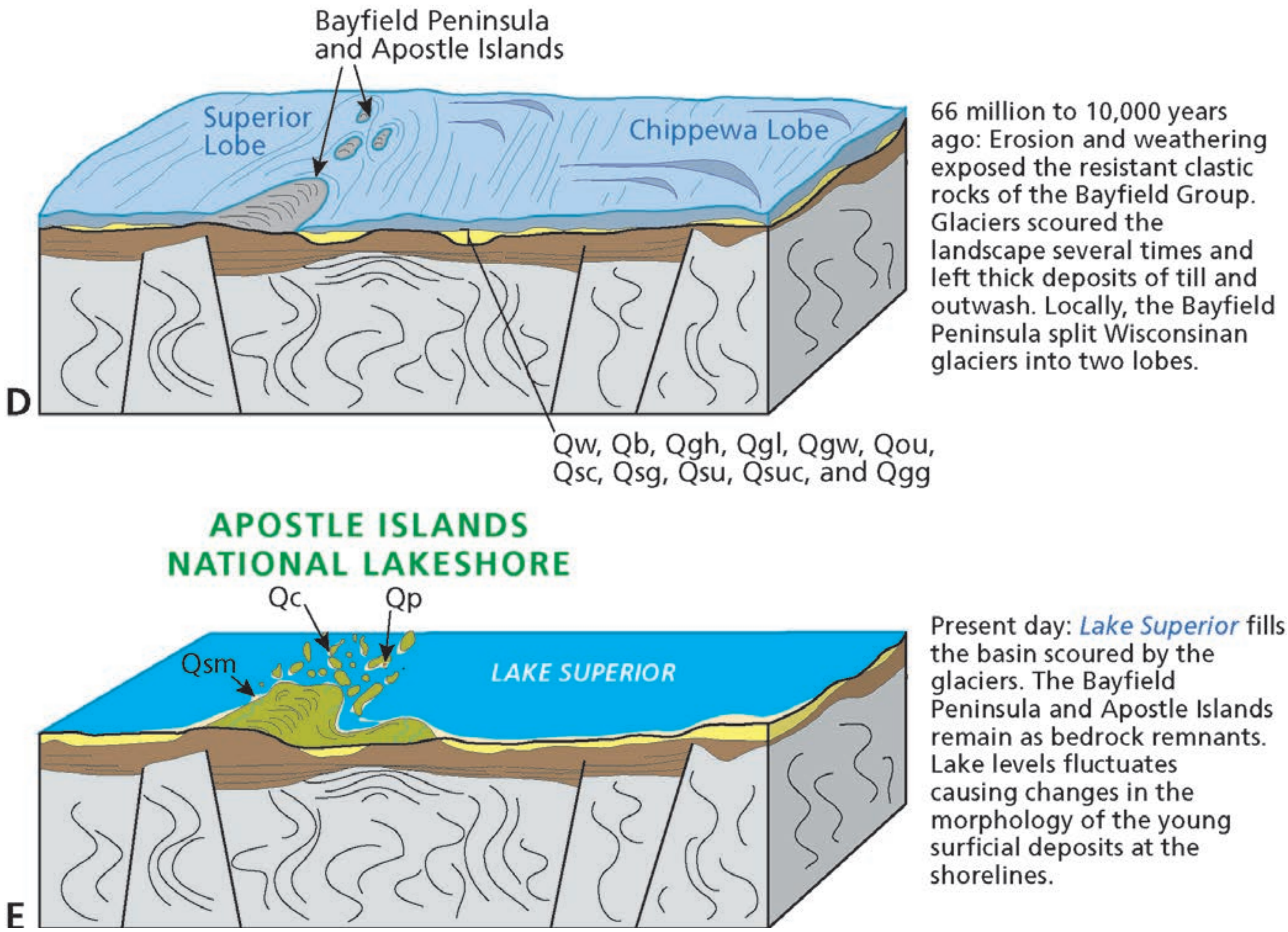
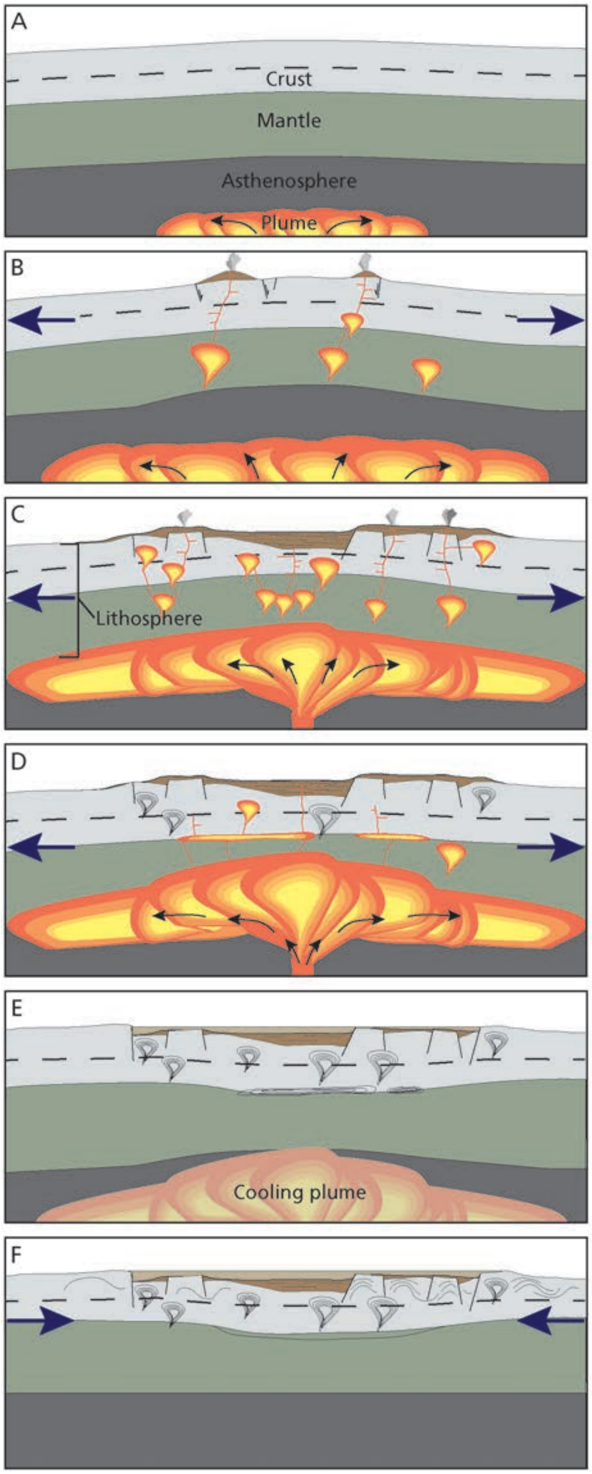


Figure 33 D–E. Schematic graphics illustrating the evolution of the landscape and geologic foundation of Apostle Islands National Lakeshore (continued). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) using information from Ojakangas et al. (2011), Nuhfer and Dalles (2004), Clayton (1984), and Cannon et al. (1999).

cross-beds indicate the Orienta Sandstone collected in channels of northeastward-flowing streams. As the accumulating sands began to fill the local basin, shallow lakes surrounded by sandy beaches formed in the Apostle Islands area. Waves, wind, and streams reworked the sediments to a fine-grain size and nearly pure-quartz composition of the Devils Island Sandstone (**PCdi**) (Cannon et al. 1999; Nuhfer and Dalles 2004; Galston 2008).

After the deposition of the Devils Island Sandstone, the area subsided again, allowing further accumulation of sediment (fig. 33C). Streams resumed their northeasterly flows across the landscape and deposited the feldspar-rich sediments of the Chequamegon Sandstone (**PCch**). These streams were likely sediment-choked, shallow, and braided across several simultaneous or successive channels (Nuhfer and Dalles 2004). As sediment from one channel built up high enough, streamflow was diverted to a lower level, thus accumulating a nearly continuous blanket of thick sand, conglomerate, and clay-poor deposits throughout the area (Nuhfer and Dalles 2004).

At the end of Bayfield Group deposition, fluvial and lacustrine sediment totaled more than 800 m (2,600 ft) in thickness. Encroaching Paleozoic seas deposited thick layers of sediments atop the Bayfield Group (Thornberry-Ehrlich 2013; Nuhfer and Dalles 2004; Richard Ojakangas, written communication, 12 January 2015), then the entire stack of rocks was buried and slightly deformed (Nuhfer and Dalles 2004). Deformation may have occurred as a result of compression during the Grenville Orogeny east of the rift (fig. 34F).



1.110 billion years ago: The crust moved upward, forming a dome as a plume of molten material rose from the Earth's mantle.

1.108 billion years ago: Extension reached a point where thinning of the crust and upper mantle occurred. Molten material rose and erupted as lava from 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 as blocks of crust moved downward along faults. Massive volumes of lava erupted 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: Volcanism ceases. The cooling plume draggec the lithosphere downward and the surface sagged. The added weight of lavas and sediments contributed to sagging.
The Bayfield Group was deposited in the rift basins.

1.060 billion years ago: After extension ceased, compression, possibly from the Grenville Orogeny to the east, reactivated zones of weakness (older faults) and caused regional folding.

Figure 34. Schematic graphics illustrating the evolution of the Midcontinent rift. The rift developed in a series of events: A–F. Large arrows indicate the tectonic stress direction (e.g., extension or compression). The graphics are not to scale and do not represent any particular cross section through the rift. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Hinze et al. (1997, figure 19).

The third stage in rift history, which began about 1.08 billion years ago and culminated at about 1.06 billion years ago, was a compressional event coincident with major mountain building during the Grenville orogeny that ultimately resulted in the assembly of the supercontinent Rodinia (Cannon 1994). The normal faults along the Midcontinent rift were reversed, and the central graben was uplifted relative to the rift flanks between 1.04 billion and 950 million years ago. This was after and perhaps concurrent with Bayfield Group deposition (Ojakangas et al. 2011; Thornberry-Ehrlich 2013).

During the Neoproterozoic, approximately 760 million years ago, in a setting similar to the Midcontinent rift, tectonic forces (extension) began to pull the supercontinent Rodinia apart. Breaking up of the supercontinent formed a basin that eventually became the Iapetus Ocean (a precursor to the Atlantic Ocean) far to the east of the Lake Superior region, which was in the center of the North American craton (fig. 36). Rifting was completed by about 541 million years ago (start of the Paleozoic Era), and the Iapetus Ocean separated ancient North America (Laurentia) from the other continents (Volkert and Drake 1999).

541 Million to 66 Million Years Ago (Paleozoic and Mesozoic Eras)—Burial and a Missing Rock Record

After millions of years of tectonic stability at the beginning of the Paleozoic, tectonic unrest commenced once again along the eastern margin of North

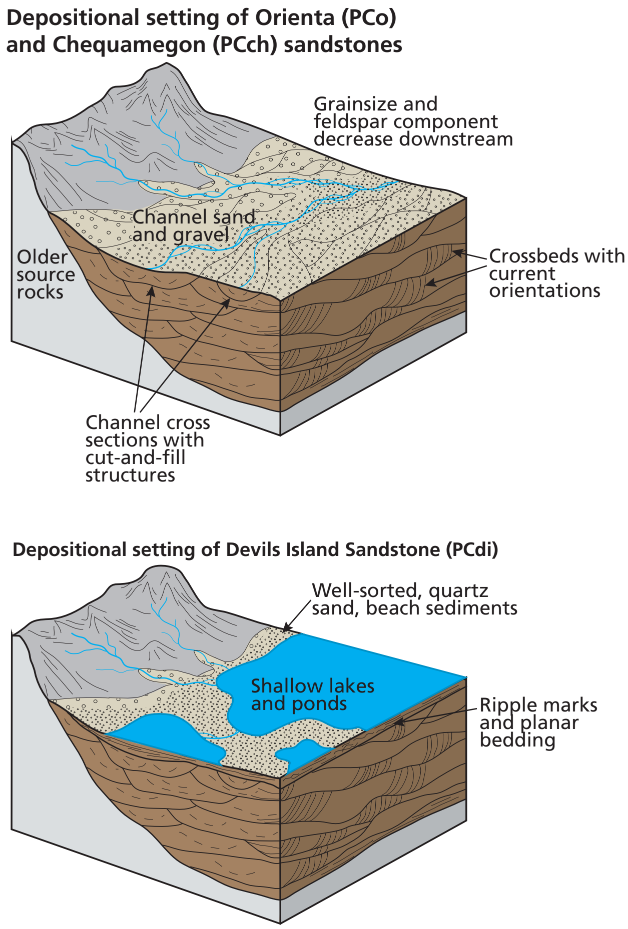


Figure 35. Depositional settings of the Bayfield Group. Sediment-choked, braided streams deposited the Orienta and Chequamegon sandstones (PCo and PCch). The Devils Island Sandstone (PCdi) was deposited as beach, dune, and shallow-lake sands. Sedimentary structures resulting parallel and perpendicular to flow are show in the cross sections. Colors in cross section are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps; they also correspond to the colors on the Map Unit Properties Table (in pocket). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Nuhfer and Dalles (2004, figure 4).

America. A series of landmass collisions and mountain-building orogenies throughout the Paleozoic Era built the Appalachian Mountains and culminated in the formation of another supercontinent—Pangaea. At this time, the Bayfield Group remained buried under thick piles of sediment in northern Wisconsin.

During the Triassic Period, approximately 200 million years ago, the supercontinent Pangaea began to rift apart forming fault-bounded rift basins along the eastern coast of North America. Unlike the

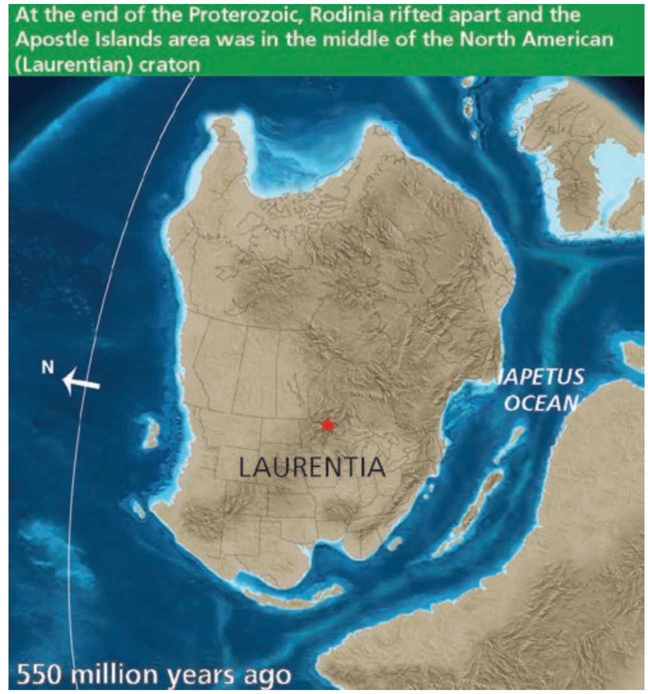


Figure 36. Paleogeographic map of North America 550 million years ago. At this time, northern Wisconsin was in the center of the craton and the sediments of the Bayfield Group were deeply buried. Red star indicates approximate present-day location of Apostle Islands National Lakeshore. Graphic compiled by Trista L. Thornberry-Ehrlich (Colorado State University). Base paleogeographic map by Ron Blakey (Colorado Plateau Geosystems), available at http://cpgeosystems.com/nam.html (accessed 8 May 2015).

Proterozoic Midcontinent rift, this rifting resulted in the development of an ocean (Atlantic Ocean). The rifting led to the configuration of continents that persists today and the Atlantic Ocean continues to widen. The effects of these events were focused east of northern Wisconsin.

66 Million Years Ago to Present (Cenozoic Era)—Erosion, Ice Age Glaciation, and Rebound

Rocks from much of the Paleozoic, all of the Mesozoic, and early Cenozoic eras does not exist in this part of Wisconsin. Whatever rocks were deposited atop the Bayfield Group were stripped away by erosion and weathering over millennia. Approximately 2.5 million years ago, after hundreds of millions of years of erosion and weathering, northeastward-flowing, ancestral streams had eroded valleys down into the sandstones of the Mesoproterozoic Bayfield Group in the Apostle Islands area. The rock types, textures, and grain sizes

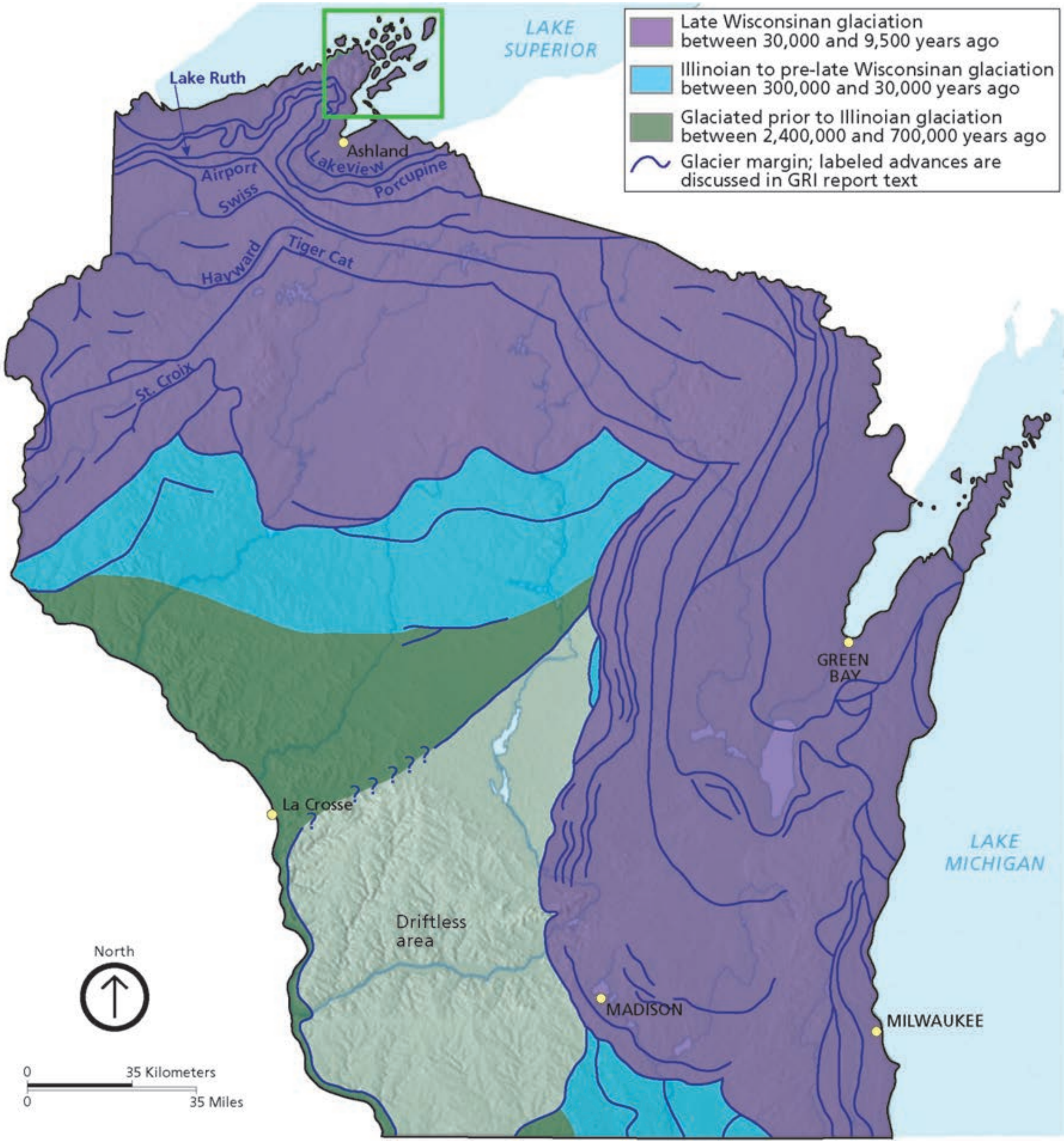


Figure 37. Glaciations in Wisconsin. Glacial ice advanced and retreated many times over the landscape. Each advance obscured or obliterated evidence of previous advances, thus the record is best for the most recent major glaciation—the Wisconsinan (purple on graphic). A large area in the southwestern part of the state, called the "driftless area," was not covered by glacial ice. "Drift" is rock material transported and deposited by either a glacier or meltwater. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Syverson and Colgan (2004) and Ojakangas et al. (2011, figure 9) and. Shaded-relief base map by Tom Patterson (National Park Service), available at: http://www.shadedrelief.com/physical/index.html (accessed 18 August 2014).

of the sandstones (directly related to their depositional setting) probably influenced stream activity and the location of these early valleys. During deposition, major channels of the Mesoproterozoic streams would have carried coarser sediments, creating more resistant sandstone layers while adjacent smaller streams would have deposited finer, more easily eroded materials.

Those streams preferentially incised the softer, more easily eroded layers. As ridges divising ancient watershed eroded away, isolated hills (underlain by the coarser sandstones) remained. Those hills are likely the precursors to the Apostle Islands (Nuhfer and Dalles 2004).

As described in the "Glacial Features" section, during

Table 2. Pleistocene glacial advances recorded in the Apostle Islands region.

Glacial Advance	Years Before Present	Surface Elevation	Associated Glacial Lakes	Associated Surficial Geologic Units
St. Croix	20,000	Unknown	None documented	Copper Falls Formation (Qsc, Qsg, Qsu, Qsuc, and Qgg)
Tiger Cat	<18,000?	Unknown	None documented	
Hayward	16,000?	375 m (1,230 ft)	Grantsburg, Upham	
Swiss	14,000?	306 m (1,004 ft)	Grantsburg, Upham	
Airport	12,300	Unknown	None documented	
Lake Ruth	11,500	380–390 m (1,250–1,280 ft)	Nemadji?	
Porcupine	11,000	Unknown	Nemadji, Ontonagon, Upham	Miller Creek Formation (Qw, Qb, Qgh, Qgl, Qgw, and Qou)
Lake View	<10,000	Unknown	Nemadji, Ontonagon, Ashland, Brule	

Sources: Clayton (1984, 1985) and Nuhfer and Dalles (2004)

the Pleistocene Epoch, global climate shifts brought alternating cold periods—ice ages—and relatively warm periods (similar to modern climate). Continental ice sheets descended south from the Arctic, reshaping the landscape. The impacts to the Apostle Islands and Lake Superior were extensive. Successive glaciations tend to obliterate or obscure evidence of former glaciations. The record of glacial effects at the Bayfield Peninsula and Apostle Islands only extends back to about 30,000 years ago, but adjacent areas provide evidence that glaciers advanced and retreated across the Lake Superior basin many times before then (fig. 37; Nuhfer and Dalles 2004).

Twenty-thousand years ago, at the time of the St. Croix advance (table 2), glacial ice flowed southwestward into an area of isolated hills that were the precursors to the Apostle Island. The glaciers flowed into the valleys first and were divided into lobes (Superior Lobe to the west and Chippewa sublobe to the east) by the hills and the highlands that would become the Bayfield Peninsula. Subsequent flows of thicker ice likely covered everything (fig. 33D), scouring the hills to bare rock. Stones plucked from other areas were scraped over the landscapes along the base of the flowing glaciers forming glacial grooves and striations. A series of other local advances—named for areas where they were described; Tiger Cat, Hayward, Swiss, Airport, Lake Ruth, Porcupine, and Lake View—followed the St. Croix advance (Clayton 1984). The Airport advance was the last glacial advance to cover the interior of the Bayfield Peninsula at about 12,300 years ago (Clayton 1984; Ojakangas et al. 2011).

As climate warmed in the late Pleistocene and early Holocene epochs, the 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 flowed through a southerly outlet in the ice. The modern basins in which these lakes stood lent their names to the glacial lakes (e.g., Lake Nemadji, Lake Brule, Lake Ashland, and Lake Ontonagon). The glacial lakes along the southern edge of the retreating ice eventually coalesced to form Lake Superior (Clayton 1984). Lacustrine sediments from Lake Superior and earlier lakes were deposited on top of glacial tills throughout the area (Scholz 1984).

Atop the Bayfield Peninsula and Apostle Islands, which were relatively high topography, glacial ice was thinner. The thinner ice melted faster than thicker ice in adjacent areas and provided a basin for some of the meltwater streams that flowed down the St. Croix spillway. Eventually, this channel drained Lake Superior, which then stood about 145 m (475 ft) higher than its present level. A high-water stage of Lake Superior followed each glacial advance and retreat. The outlet for Glacial Lake Duluth (the best developed of the high-level stages and beaches of Lake Superior) was near Winneboujou, Wisconsin. A 30-m- (100-ft-) deep channel incised when the lake drained about 9,900 years ago via the Bois-Brule River outlet into the St. Croix River (Clayton 1984; Ojakangas et al. 2011). At the time, water flowed south through the channel. Today, the modern Brule River flows as an underfit stream (a stream too small to have carved its current valley) through this large notch northward into Lake Superior.

The lake was at its highest level, 335 m (1,100 ft), 9,500 years ago (Ojakangas et al. 2011). At least five lower levels occurred, but evidence of them was obscured by wave action. At each temporary shoreline, wave-cut lake terraces formed, recording previous elevations: 145 m (475 ft), 116 m (380 ft), 87 m (285 ft), 67 m (220 ft), 37 m (120 ft), and 6 m (20 ft) above the present normal elevation of Lake Superior at 183 m (602 ft) above sea level (Clayton 1984; Nuhfer and Dalles 2004). Approximately 8,000 years ago, during the Houghton stage, Lake Superior's elevation was nearly 73 m (240 ft) below the present lake level (Farrand 1960; Nuhfer and Dalles 2004). During the height of the Nipissing stage about 4,500 years ago, the water level was about 186 m (610 ft) above sea level. At this time, its outlet (Port Huron) was downcut, and the level of Lake Superior fell until about 2,200–2,100 years ago when water in Lake Huron dropped below Sault Ste. Marie and became a separate basin. This occurred as a result of uneven isostatic rebout of the St. Marys River outlet to Lake Superior (Hansel et al. 1985; Bona 1990; Larsen 1999).

The Apostle Islands weathered in response to relentless wave energy from Lake Superior. As lake levels continuously fluctuate, the record of shoreline features at different levels are either perched on the islands or remain submerged offshore. As described in the "Lake Superior Shoreline" section, the modern shorelines (fig. 33E) are in a near constant state of flux as bedrock and glacial-till bluffs are worn away and sediment transported around, among, and beyond the Apostle Islands. The double tombolo joining Presque Isle with Stockton Island may have begun forming as recently as 2,500 years ago; however, pollen records from the bog there extend back 6,000 years (Kraft 1982; Swain and Winkler 1983; Bona 1990). Dated cores from bogs and drowned trees reveal longstanding lake-level highs at about 1,100, 400, and 200 radiocarbon years before present and low episodes at about 650 and 350 years before present (Larsen et al. 1999). Islands such as Gull Island have nearly washed away in strong storms. Radiocarbon ages of peat in bog-filled swales on Long Island are as old as 520±70 years before present (Bona 1990). This age is likely younger than the true age of the barrier system (Bona 1990), but is a testament to the constancy of change and dynamic nature of features at Apostle Islands National Lakeshore.

Geologic Map Data

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

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, these maps portray the spatial distribution and temporal relationships of rocks and unconsolidated deposits. Geologic maps can be divided into two primary types: surficial and bedrock. Surficial geologic maps typically encompass deposits that are unconsolidated and formed during the past 2.6 million years (the Quaternary Period). Surficial map units are differentiated by geologic process or depositional environment. Bedrock geologic maps encompass older, typically more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type.

Geologic maps often depict geomorphic features, structural interpretations (such as faults or folds), and locations of past geologic hazards that may be susceptible to future activity. Anthropogenic features such as mines or quarries, as well as observation or collection locations, may be indicated on geologic maps. The American Geosciences Institute website, http://www.americangeosciences.org/environment/publications/mapping (accessed 10 April 2015), provides more information about geologic maps and their uses.

There are two sets of GRI GIS data for Apostle Islands National Lakeshore. One is a bedrock geology map (apis_geology.mxd) and the other is a surficial "Pleistocene" geology map (aipg_geology.mxd).

Source Maps

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

Cannon, W. F., L. G. Woodruff, S. W. Nicholson, C. A. Hedgman, and R. D. Barber-Delach. 1999. Digital bedrock geologic map of the Ashland and northern part of the Ironwood 30' × 60' quadrangles, Wisconsin and Michigan (scale 1:100,000). Open-File Report OF 99-546. US Geological Survey, Reston Virginia. http://pubs.er.usgs.gov/publication/ofr99546 (accessed 12 May 2014).

Clayton, L. 1985. Pleistocene geology of the Superior region, Wisconsin (scale 1:250,000). Regional Map Series 3. Wisconsin Geological and Natural History Survey, Madison, Wisconsin.

Nicholson, S. W., W. F. Cannon, L. G. Woodruff, and C. L. Dicken. 2004a. Bedrock geologic map of the Port Wing, Solon Springs, and parts of the Duluth and Sandstone 30' × 60' quadrangles, Wisconsin (scale 1:100,000). Open-File Report 2004-1303. US Geological Survey, Reston, Virginia. http://pubs.er.usgs.gov/publication/ofr20041303 (accessed 12 May 2014).

Nicholson, S. W., C. L. Dicken, M. P. Foose, and J. Mueller. 2004b. Integrated geologic map databases for the United States, the upper Midwest states: Minnesota, Wisconsin, Michigan, Illinois, and Indiana (scale 1:500,000). Open-File Report 2004-1355. US Geological Survey, Reston, Virginia. http://pubs.er.usgs.gov/publication/ofr20041355 (accessed 12 May 2014).

GRI GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available at http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm (accessed 10 April 2015). This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for Apostle Islands National Lakeshore using data model version 2.1. The GRI Geologic Maps website, http://www.nature.nps.gov/geology/inventory/geo_maps.cfm (accessed 10 April 2015), provides more information about GRI map products.

GRI digital geologic data are included on the attached CD and are available through the NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/App/Reference/Search?SearchType=Q; accessed 10 April 2015). Enter "GRI" as the search text and select a park from the unit list.

The following components are part of the data set:

- A GIS readme file (apis_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information;
- Data in ESRI geodatabase GIS format;
- Layer files with feature symbology (tables 3 and 4);
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information document (apis_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures;
- ESRI map documents (apis_geology.mxd and aipg_geology.mxd) that display the digital geologic data; and
- KML/KMZ versions of the data viewable in Google Earth (tables 3 and 4).

GRI Map Posters

Two posters (in pocket) illustrate each of the GRI GIS data sets draped over aerial imagery of the park and surrounding area. Not all GIS feature classes are included on the posters (tables 3 and 4). Geographic information and selected park features have been added to the posters. Digital elevation data and added geographic information are not included in the GRI GIS data set, but are available online from a variety of sources. Contact GRI for assistance locating these data.

Map Unit Properties Tables

The Map Unit Properties Tables list the geologic time division, symbol, and a simplified description for each of the map units in the GRI GIS data sets. Following the structure of the report, the tables summarize the geologic features, processes, resource management issues, and history associated with each map unit. There are separate tables for the bedrock and surficial ("Pleistocene") geologic map data.

Use Constraints

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

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features on the posters. Based on the source map scales (1:100,000, 1:250,000, and 1:500,000) and US National Map Accuracy Standards, geologic features represented in the geologic map data are horizontally within 51 m (167 ft), 127 m (417 ft), and 254 m (833 ft), respectively, of their true locations.

Table 3. Data layers in the Apostle Islands National Lakeshore bedrock geology GIS data (apis_geology.mxd; apis_geology.kmz).

Data Layer	On Poster?	Google Earth Layer?
Geologic Cross Section Lines	No	No
Geologic Attitude and Observation Points (strike and dip)	No	No
Mine Point Features (drill holes)	Yes	No
Faults	Yes	Yes
Outcrops	Yes	Yes
Geologic Contacts	Yes	Yes
Geologic Units	Yes	Yes

Table 4. Data layers in the Apostle Islands National Lakeshore Pleistocene geology GIS data (aipg_geology.mxd; aipg_geology.kmz).

Data Layer	On Poster?	Google Earth Layer?
Glacial Feature Points (direction of glacial stream flow)	Yes	No
Glacial Feature Lines (drumlins and glacial ridges)	Yes	Yes
Geologic Line Features (abandoned beach and wave-cut bluffs; river channel cutbanks)	Yes	Yes
Geologic Contacts	Yes	Yes
Geologic Units	Yes	Yes

Glossary

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

accretion (streams). The filling-up of a stream channel as a result of such factors such as silting or wave action.

adit. A horizontal passage into a mine from the surface.

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

alluvial fan. A low, relatively flat to gently sloping, fan-shaped mass of loose rock material deposited by a stream, especially in a semiarid region, where a stream issues from a canyon onto a plain or broad valley floor.

alluvium. Stream-deposited sediment.

anticline. A fold, generally convex upward ("A"-shaped) whose core contains the stratigraphically older rocks.

aquiclude. A saturated geologic unit that is incapable of transmitting significant quantities of water under ordinary hydraulic gradients. Replaced by the term "confining bed."

aquifer. A rock or sedimentary unit that is sufficiently porous to hold water, sufficiently permeable to allow water to move through it, and saturated to some level.

aragonite. A carbonate (carbon + oxygen) mineral of calcium, $CaCO_3$; the second most abundant cave mineral after calcite, differing from calcite in its crystal structure.

arenite. A general term for sedimentary rocks composed of sand-sized fragments.

arête. A sharp-edged rocky ridge, commonly present above snowline in rugged, glacially sculpted mountains; results from the continued backward growth of the walls of adjoining cirques.

argillaceous. Pertaining to, largely composed of, or containing clay-size particles or clay minerals.

arkose. A commonly coarse-grained, pink or reddish sandstone consisting of abundant feldspar minerals.

artesian. Describes groundwater confined under hydrostatic pressure.

artesian pressure. Hydrostatic pressure of artesian water, often expressed in terms of pounds per square inch at the land surface, or in terms of the height (in feet above the land surface) of a column of water that would be supported by the pressure.

artesian spring. A spring from which water flows under artesian pressure, usually through a fissure or other opening in the confining bed above the aquifer.

artesian system. Any system incorporating the following: a water source, a body of permeable rock bounded by bodies of distinctly less permeable rock, and a structure enabling water to percolate into and become confined in the permeable rock under pressure distinctly greater than atmospheric.

artesian well. A well that taps confined groundwater. Water in the well rises above the level of the top of the aquifer under artesian pressure.

asthenosphere. Earth's relatively weak layer below the rigid lithosphere where isostatic adjustments take place, magmas may be generated, and seismic waves are strongly attenuated; part of the upper mantle.

astronomical tide. The periodic rise and fall of a body of water resulting from gravitational interactions between the Sun, Moon, and Earth. Synonymous with "tide," but used to emphasize the absence of atmospheric influences.

back barrier. The landward side of a barrier island.

backwasting. Wasting (gradual erosion) that causes a slope to retreat without changing its gradient.

backwater. A body of water that is parallel to a river but is stagnant or little affected by the river's currents.

bank. A submerged ridge of sand in the sea, a lake, or a river, usually exposed during low tide or low water.

barrier island. A long, low, narrow island consisting of a ridge of sand that parallels the coast.

basalt. A volcanic rock that is characteristically dark in color (gray to black), contains approximately 53% silica or less, and is rich in iron and magnesium.

base flow. Streamflow supported by groundwater and not attributed to direct runoff from precipitation or snow melt.

basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie rocks exposed at the surface, commonly sedimentary. In many regions the basement is of Precambrian age, but it may be much younger. Also, Earth's crust below sedimentary deposits that extends down to the Mohorovicic discontinuity.

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

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

bathymetry. The measurement of ocean or lake depths and the charting of the topography of the ocean or lake floor.

beach. The unconsolidated material at the shoreline that covers a gently sloping zone, typically with a concave profile, extending landward from the low-water line to the place where there is a definite change in material or physiographic form (e.g., a cliff), or to the line of permanent vegetation (usually the effective limit of the highest storm waves).

beach face. The section of the beach normally exposed to the action of wave uprush.

bed. The smallest sedimentary stratigraphic unit, commonly ranging in thickness from about 1 cm (0.4 in) to 1 to 2 m (40 to 80 in) and distinguishable from beds above and below.

bedding. Depositional layering or stratification of sediments.

bedrock. Solid rock that underlies unconsolidated sedimentary deposits and soil.

berm. A low, impermanent, nearly horizontal or landward-sloping bench, shelf, or ledge above the high-water line on a beach.

block (fault). A crustal unit bounded completely or partially by faults.

blowout. A general term for a small saucer-, cup-, or trough-shaped hollow or depression formed by wind erosion on a preexisting dune or other sand deposit, especially in an area of shifting sand or loose soil, or where protective vegetation is disturbed or destroyed.

body fossil. Evidence of past organisms such as bones, teeth, shells, or leaf imprints.

braided stream. A sediment-clogged stream that forms multiple channels that divide and rejoin.

breakdown. Collapse of a cave ceiling or walls of a cave. Also, the accumulation of debris thus formed.

breakwater. An offshore, generally shore-parallel structure that breaks the force of the waves.

breccia. A coarse-grained, generally unsorted sedimentary rock consisting of cemented angular clasts more than 2 mm (0.08 in) across.

burrow. A tubular or cylindrical hole or opening, made in originally soft or loose sediment by a mud-eating worm, mollusk, or other invertebrate; may be later filled with clay or sand and preserved.

calcareous. Describes a substance that contains calcium carbonate. When applied to a rock name it implies that as much as 50% of the rock is calcium carbonate.

calcium carbonate. CaCO3. A solid occurring in nature as primarily calcite and aragonite.

calcite. A carbonate (carbon + oxygen) mineral of calcium, $CaCO_3$; calcium carbonate. It is the most abundant cave mineral.

carbonate. A mineral group composed of carbon and oxygen plus an element or elements; for example calcite, CaCO3; and dolomite, CaMg(CO3)2.

carbonate rock. A rock, for example, limestone, calcite, and dolomite, that consist primarily of carbonate minerals.

cement (sedimentary). Mineral material, usually chemically precipitated, that occurs in the spaces among the individual grains of a sedimentary rock, thus binding the grains together.

cementation. The process by which clastic sediments become lithified or consolidated into hard, compact rocks, usually through deposition or precipitation of minerals in the spaces among the individual grains of the sediment; may occur simultaneously with sedimentation or at a later time.

chemical weathering. Chemical breakdown of minerals at Earth's surface via reaction with water, air, or dissolved substances; commonly results in a change in chemical composition providing more stability in the current environment.

chert. An extremely hard sedimentary rock with conchoidal fracturing, consisting mostly of interlocking crystals of quartz.

chronology. The arrangement of events in their proper sequence in time.

clast. An individual constituent, grain, or fragment of a rock or unconsolidated deposit, produced by the mechanical or chemical disintegration of a larger rock mass.

clastic. Describes rocks or sediments made of fragments of preexisting rocks.

clay. Minerals and sedimentary fragments that are less than 1/256 mm (0.00015 in) across.

claystone (sedimentary). An indurated rock with more than 67% clay-sized minerals.

cleavage. The tendency of a mineral to break along planes of weak bonding.

coarse-grained. Describes a crystalline rock and texture in which the individual minerals are relatively large, specifically an igneous rock whose particles have an average diameter greater than 5 mm (0.2 in). Also, describes sediment or sedimentary rock and texture in which the individual constituents are easily seen with the unaided eye, specifically sediment or rock whose particles have an average diameter greater than 2 mm (0.08 in).

colluvium. A loose, heterogeneous, and incoherent mass of rock fragments and soil material deposited via surface runoff or slow continuous downslope creep; usually collects at the base of a slope or hillside, but includes loose material covering hillsides.

compression. A decrease in volume of material (including Earth's crust) as it is pressed or squeezed together.

confined aquifer. An aquifer bounded above and below by confining beds. An aquifer containing confined groundwater.

confined groundwater. Groundwater under pressure significantly greater than that of the atmosphere. Its upper surface is the bottom of a confining bed.

confining bed. A body of relatively impermeable or distinctly less permeable material stratigraphically adjacent to one or more aquifers. Replaced the term "aquiclude."

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

contact. The surface between two types or ages of rocks.

continental drift. A term for the process by which continents move relative to one another; it is a consequence of plate tectonics.

continental crust. Earth's crust that is rich in silica and aluminum and underlies the continents and the continental shelves; ranges in thickness from about 25 km (15 mi) to more than 70 km (40 mi) under mountain ranges, averaging about 40 km (25 km) thick.

continental shield. A large area of exposed basement at the interior of a continent, commonly with a very gently convex surface, surrounded by sediment-covered platforms. The rocks of virtually all shield areas are Precambrian.

coral. Any of a large group of bottom-dwelling, sessile, marine invertebrate organisms (polyps) that belong to the class Anthozoa (phylum Cnidaria), characterized by production of an external skeletons of calcium carbonate; may exist as solitary individuals or grow in colonies.

Range: Abundant in the fossil record in all periods later than the Cambrian.

core (drill). A cylindrical section of rock or sediment. usually 5–10 cm (2–4 in) across and up to several meters long, taken as a sample of the interval penetrated by a core bit, and brought to the surface for geologic examination and/or laboratory analysis.

craton. The relatively old and geologically stable interior of a continent.

creep. The slow, imperceptible downslope movement of mineral, rock, and soil particles under gravity.

cross-bed. A single bed, inclined at an angle to the main planes of stratification; the term is commonly restricted to a bed that is more than 1 cm (0.4 in) thick.

cross-bedding. Uniform to highly varied sets of inclined beds deposited by wind or water that indicate flow conditions such as direction and depth.

cross section. A graphic interpretation of geology, structure, or stratigraphy based on mapped and measured geologic extents and attitudes, depicted in a vertical plane (i.e., a cut or profile view).

crust. Earth's outermost layer or shell.

crystalline. Describes a regular, orderly, repeating geometric structural arrangement of atoms.

debris flow. A moving mass of rock fragments, soil, and mud, with more than half of the particles larger than sand size. Slow debris flows may move less than 1 m (3 ft) per year; rapid ones reach 160 km per hour (100 mi per hour).

deformation. The process of folding, faulting, shearing, or fabric development in rocks as a result of Earth stresses.

delta. The low, nearly flat, alluvial tract of land at or near the mouth of a river, commonly forming a triangular or fan-shaped plain of considerable area; resulting from the accumulation of sediment supplied by the river in such quantities that it is not removed by tides, waves, and currents.

differential erosion. Erosion that occurs at irregular or varying rates due to differences in the resistance and hardness of surface material: softer and weaker rocks are rapidly worn away; harder and more resistant rocks remain to form ridges, hills, or mountains.

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

discharge. The rate of flow of surface water or groundwater at a given moment, expressed as volume per unit of time.

displacement. The relative movement of the two sides of a fault; also, the specific amount of such movement.

divergent plate boundary. A boundary between two plates that are moving apart, characterized by mid-ocean ridges at which sea-floor spreading occurs.

dolomite (mineral). A carbonate (carbon + oxygen) mineral of calcium and magnesium, $CaMg(CO_3)_2$.

dolomite (rock). A carbonate sedimentary rock containing more than 50% of the mineral dolomite (calcium-magnesium carbonate).

downcutting. Stream erosion in which cutting is directed primarily downward, as opposed to laterally.

drainage. The manner in which the waters of an area flow off in surface streams or subsurface conduits; also, the processes of surface drainage of water from an area by streamflow and sheet flow, and the removal of excess water from soil by downward flow.

drainage basin. A region or area bounded by a drainage divide and occupied by a drainage system, specifically the tract of country that gathers water originating as precipitation and contributes it to a particular stream channel or system of channels, or to a lake, reservoir, or other body of water.

dredge (engineering). A floating machine for excavating sedimentary material from the bottom of a body of water.

drift. All rock material (clay, silt, sand, gravel, and boulders) transported and deposited by a glacier, or by running water emanating from a glacier.

drumlin. A low, smoothly rounded, elongated oval hill, mound, or ridge of till that formed under the ice margin and was shaped by glacial flow; the long axis is parallel to the direction of ice movement.

dune. A low mound or ridge of sediment, usually sand, deposited by the wind.

ephemeral stream. A stream that flows briefly, only in direct response to precipitation, and whose channel is always above the water table.

erosion. The general process or group of processes that loosen, dissolve, wear away, and simultaneously move from one place to another, the materials of Earth's crust; includes weathering, solution, abrasive actions, and transportation, but usually excludes slope movements.

erratic. A rock fragment carried by glacial ice deposited at some distance from the outcrop from which it was derived, and generally, though not necessarily, resting on bedrock of different lithology.

escarpment. A steep cliff or topographic step resulting from vertical displacement on a fault or as a result of slope movement or erosion. Synonymous with "scarp."

estuary. The seaward end or tidal mouth of a river where freshwater and seawater mix.

exfoliation. The spalling, peeling, or flaking of layers or concentric sheets from an exposed rock mass caused by a change in heat or a reduction in pressure when overlying rocks erode away.

extension. Deformation of Earth's crust whereby rocks are pulled apart.

extrusion. The emission of lava onto Earth's surface; also, the rock so formed.

fault. A break in rock characterized by displacement of one side relative to the other.

feldspar. A group of abundant silicate (silicon + oxygen) minerals, comprising more than 60% of Earth's crust and occurring in all types of rocks.

feldspathic. Describes a rock containing feldspar.

felsic. Derived from *fel*dspar + *si*lica to describe an igneous rock having abundant light-colored minerals such as quartz, feldspars, or muscovite; also, describes those minerals.

fetch. The area of the ocean surface over which a constant and uniform wind generates waves.

fine-grained. Describes sediment or sedimentary rock and texture in which the individual constituents are too small to distinguish with the unaided eye, specifically sediment or rock whose particles have an average diameter less than 1/16 mm (0.002 in), that is, silt-size particles and smaller. Also, describes a crystalline or glassy rock and texture in which the individual minerals are relatively small, specifically an igneous rock whose particles have an average diameter less than 1 mm (0.04 in).

fissure. A fracture or crack in rock along which there is a distinct separation; commonly filled with mineral-bearing materials.

fissure (volcanic). An elongated fracture or crack at the surface from which lava erupts.

fissure vent. A volcanic conduit having the form of a crack or fissure at Earth's surface.

floodplain. The surface or strip of relatively smooth land composed of alluvium and adjacent to a river channel, constructed by the present river in its existing regimen and covered with water when the river overflows its banks. A river has one floodplain and may have one or more terraces representing abandoned floodplains.

fluvial. Of or pertaining to a river or rivers.

fluvial channel. A natural passageway or depression produced by the action of a stream or river.

fold. A curve or bend in an originally flat structure, such as a rock stratum, bedding plane, or foliation; usually a product of deformation.

footwall. The lower wall of a fault.

foreshore. The part of the beach face that lies between the berm crest and the low-water line; it is regularly covered and uncovered by the rise and fall of the tide and is shaped by tides and waves.

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

fossil. A remain, trace, or imprint of a plant or animal that has been preserved in the Earth's crust since some past geologic time; loosely, any evidence of past life.

fracture. The breaking of a mineral other than along planes of cleavage. Also, any break in a rock such as a crack, joint, or fault.

frost wedging. A type of mechanical disintegration, splitting, or breakup of a rock by which jointed rock is pried and dislodged by ice acting as a wedge.

geodetic surveying. Surveying that takes into account the figure and size of Earth, with corrections made for curvature; used where the areas or distances involved are so great that the desired accuracy and precision cannot be obtained by plane (ordinary field and topographic) surveying.

geomorphology. The study of the general configuration of surface landforms and their relationships to underlying structures, and of the history of geologic changes as recorded by these surface features.

glaciolacustrine. Pertaining to, derived from, or deposited in glacial lakes, especially referring to deposits and landforms composed of suspended material transported by meltwater streams flowing into lakes bordering a glacier.

Gondwana. The late Paleozoic continent of the Southern Hemisphere and counterpart of Laurasia of the Northern Hemisphere; both were derived from the supercontinent Pangaea.

gradient. A degree of inclination (steepness of slope), or a rate of ascent or descent, of an inclined part of Earth's surface with respect to the horizontal; expressed as a ratio (vertical to horizontal), a fraction (such as m/km or ft/mi), a percentage (of horizontal distance), or an angle (in degrees).

granite. A coarse-grained, intrusive igneous rock in which quartz constitutes 10%–50% of the felsic ("light-colored") components and the alkali feldspar/total feldspar ratio is generally restricted to the range of 65% to 90%; perhaps the best known of all igneous rocks.

graben. An elongated, downdropped trough or basin, bounded on both sides by high-angle normal faults that dip toward one another.

gravel. An unconsolidated, natural accumulation of typically rounded rock fragments resulting from erosion; consists predominantly of particles larger than sand; that is, greater than 2 mm (1/12 in) across.

groundwater. That part of subsurface water that is in the zone of saturation, including underground streams.

hanging wall. The upper wall of a fault.

hematite. An oxide mineral composed of oxygen and iron, Fe2O3.

heterogeneous. Consisting of dissimilar or diverse ingredients or constituents.

hoodoo. A bizarrely shaped column, pinnacle, or pillar of rock, commonly produced in a region of sporadic heavy rainfall by differential weathering or erosion of horizontal strata, facilitated by layers of varying hardness and joints.

horst. An elongated, uplifted block that is bounded on both sides by normal faults that dip away from one another.

hot spot. A volcanic center, 100–200 km (60–120 mi) across, persistent for at least a few tens of millions of year, with a surface expression, commonly at the center of a plate, that indicates a rising plume of hot mantle material.

hydrostatic pressure. The pressure exerted by the water at any given point in a body of water at rest. The hydrostatic pressure of groundwater is generally due to the weight of water at higher levels in the saturated zone.

hydrology. The study of liquid and solid water properties, circulation, and distribution, on and under the Earth's surface and in the atmosphere.

igneous. Describes a rock or mineral that solidified from molten or partly molten material; also, describes processes leading to, related to, or resulting from the formation of such rocks. One of the three main classes or rocks—igneous, metamorphic, and sedimentary.

indurated. Describes a rock or soil hardened or consolidated by pressure, cementation, or heat.

intrusion. The process of emplacement of magma into preexisting rock. Also, the igneous rock mass formed.

intrusive. Pertaining to intrusion, both the process and the rock body.

isostasy. The condition of equilibrium, comparable to floating, of the units of the lithosphere above the asthenosphere.

joint. A break in rock without relative movement of rocks on either side of the fracture surface.

kame. A mound, knob, or short irregular ridge, composed of stratified sand and gravel deposited by a subglacial stream as a fan or delta at the margin of a melting glacier.

kame delta. A flat-topped, steep-sided hill of well-sorted sand and gravel deposited by a meltwater stream flowing into a proglacial or other ice-marginal lake; the proximal margin of the delta was built in contact with a glacier.

karst. A type of topography that is formed on limestone, gypsum, and other soluble rocks, primarily by dissolution. It is characterized by sinkholes, caves, and underground drainage.

lacustrine. Describes a process, feature, or organism pertaining to, produced by, or inhabiting a lake.

lagoon. A narrow body of water that is parallel to the shore and between the mainland and a barrier island; characterized by minimal or no freshwater influx and limited tidal flux, which cause elevated salinities. Also, a shallow body of water enclosed or nearly enclosed within an atoll.

lamina. The thinnest recognizable unit layer of original deposition in a sediment or sedimentary rock, differing from other layers in color, composition, or particle size; specifically a sedimentary layer less than 1 cm (0.4 in) thick and commonly 0.05–1.00 mm (0.002–0.04 in) thick. Synonymous with “lamination”; lamination is also the formation of such layers.

landslide. A collective term covering a wide variety of slope-movement landforms and processes that involve the downslope transport of soil and rock material en masse under the influence of gravity.

Laurasia. The late Paleozoic continent of the Northern Hemisphere and counterpart of Gondwana of the Southern Hemisphere; both were derived from the supercontinent Pangaea.

lava. Molten or solidified magma that has been extruded though a vent onto Earth’s surface.

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

light detection and ranging/LiDAR. A method and instrument that measures distance to a reflecting object by emitting timed pulses of light and measuring the time between emission and reception of reflected pulses; the measured interval is converted to distance.

limestone. A carbonate sedimentary rock consisting of more than 95% calcite and less than 5% dolomite.

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

lithosphere. Earth’s relatively rigid outer shell that consists of the entire crust plus the uppermost mantle. It is broken into about 20 plates, and according to the theory of plate tectonics, movement and interaction of these plates is responsible for most geologic activity.

loam. A rich permeable soil composed of a mixture of clay, silt, sand, and organic matter.

loess. Windblown silt-sized sediment.

longshore current. A current parallel to a coastline caused by waves approaching the shore at an oblique angle.

lowstand. The interval of time during one or more cycles of relative sea-level change when sea level is below the edge of the continental shelf in a given area.

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

magmatism. The development and movement of magma, and its solidification as igneous rock.

magnetite. Iron oxide. An oxide mineral composed of oxygen and iron, Fe3O4; commonly contains manganese, nickel, chromium, and titanium. A very common and widely distributed accessory mineral in rocks of all kinds and as a “heavy mineral” in sand.

mantle. The zone of the Earth below the crust and above the core.

mantle plume. A vertical cylindrical part of Earth’s mantle, hotter than its surroundings, within which larger-than-normal amounts of heat are conducted upward to form a hot spot at the Earth’s surface.

mass wasting. Dislodgement and downslope transport of a mass of rock and/or unconsolidated material under the direct influence of gravity. In contrast to “erosion,” the debris removed is not carried within, on, or under another medium. Synonymous with “slope movement.”

matrix. The fine-grained material between coarse grains in an igneous or sedimentary rock. Also refers to rock or sediment in which a fossil is embedded.

meander. One of a series of sinuous curves, bends, or turns in the course of a stream, produced by a mature stream swinging from side to side as it flows across its floodplain or shifts its course laterally toward the convex side of an original curve.

mechanical weathering. The physical breakup of rocks without change in composition.

medium-grained. Describes an igneous rock and texture in which the individual crystals have an average diameter in the range of 1 to 5 mm (0.04 to 0.2 in.). Also, describes sediment or sedimentary rock and texture in which the individual particles have an average diameter in the range of 1/16 to 2 mm (0.002 to 0.08 in), that is, sand size.

member. A lithostratigraphic unit with definable contacts; a subdivision of a formation.

metamorphic rock. Any rock derived from preexisting rocks that was altered in response to marked changes in temperature, pressure, shearing stress, and chemical environment. One of the three main classes of rock—igneous, metamorphic, and sedimentary.

metamorphism. The mineralogical, chemical, and structural changes of solid rocks, generally imposed at depth below the surface zones of weathering and cementation.

meteoric water. Water of recent atmospheric origin.

mid-ocean ridge. The continuous, generally submarine and volcanically active mountain range that marks the divergent tectonic margins in Earth's oceans.

mineral. A naturally occurring inorganic crystalline solid with a definite chemical composition or compositional range.

moraine. A mound, ridge, or other distinct accumulation of unsorted, unstratified glacial drift, predominantly till, deposited mostly by direct action of a glacier.

mud crack. A crack formed in clay, silt, or mud by shrinkage during dehydration at Earth's surface.

mud flat. A relatively level area of fine silt along a shore or around an island, alternately covered and uncovered by the tide, or covered by shallow water; a muddy tidal flat, barren of vegetation.

mudflow. A general term for a landform and process characterized by a flowing mass of predominantly fine-grained earth material possessing a high degree of fluidity during movement.

mollusk. A solitary invertebrate such as gastropods, bivalves, and cephalopods belonging to the phylum Mollusca. Range: Lower Cambrian to Holocene.

native elements. A mineral group that is composed of a single element, for example, gold, Au; or copper, Cu.

normal fault. A fault in which the hanging wall appears to have moved downward relative to the footwall; the angle of dip is usually 45°–90°.

oblique fault. A fault in which motion includes both dip-slip and strike-slip components.

oceanic crust. Earth's crust that underlies the ocean basins and is rich in iron and magnesium; ranges in thickness from about 5 to 10 km (3 to 6 mi).

orogeny. A mountain-building event.

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

outwash. Glacial sediment transported and deposited by meltwater streams.

oxidation. The process of combining with oxygen.

oxide. A mineral group composed of oxygen plus an element or elements, for example, iron in hematite, Fe_2O_3; or aluminum in corundum, Al_2O_3.

paleogeography. The study, description, and reconstruction of the physical landscape in past geologic periods.

paleontology. The study of the life and chronology of Earth's geologic past based on the fossil record.

Pangaea. A supercontinent that existed from about 300 million to about 200 million years ago and included most of the continental crust of the Earth, from which the present continents were derived by fragmentation and continental drift. During an intermediate stage of the fragmentation—between the existence of Pangaea and that of the present continents—Pangaea split into two large fragments, Laurasia in the Northern Hemisphere and Gondwana in the Southern Hemisphere.

parent material. The unconsolidated organic and mineral material from which soil forms.

parent rock. Rock from which soil, sediment, or other rock is derived.

parting. A plane or surface along which a rock readily separates.

peat. An unconsolidated deposit of semicarbonized plant remains in a water-saturated environment, such as a bog or fen, and of persistently high moisture content (at least 75%). It is an early stage or rank in the development of coal; carbon content is about 60% and oxygen content is about 30% (moisture-free).

pebble. A small rounded rock, especially a waterworn stone, between 4 and 64 mm (0.16 and 2.5 in) across.

perched aquifer. An aquifer that is separated from ("perched" above) the water table by an unsaturated zone.

period. The fundamental unit of the worldwide geologic time scale. It is lower in rank than era and higher than epoch. The geochronologic unit during which the rocks of the corresponding system were formed.

permeability. A measure of the relative ease with which a fluid moves through the pore spaces of a rock or unconsolidated deposit.

plate boundary. A zone of seismic and tectonic activity along the edges of lithospheric plates, resulting from the relative motion among plates.

plate tectonics. A theory of global tectonics in which the lithosphere is divided into about 20 rigid plates that interact with one another at their boundaries, causing seismic and tectonic activity along these boundaries.

platform. Any level or nearly level surface.

plume. A persistent, pipe-like body of hot material moving upward from Earth's mantle into the crust.

pluton. A deep-seated igneous intrusion.

plutonic. Describes an igneous rock or intrusive body formed at great depth beneath Earth's surface.

progradation. The seaward building of land as a result of sedimentary deposition.

quartz. Silicon dioxide, SiO_2. The only silicate (silicon + oxygen) mineral consisting entirely of silicon and oxygen. Synonymous with "crystalline silica."

quartzite. Metamorphosed quartz sandstone. A medium-grained, nonfoliated metamorphic rock composed mostly of quartz.

radioactivity. The spontaneous decay or breakdown of unstable atomic nuclei.

radiocarbon age. An isotopic age expressed in years and calculated from the quantitative determination of the amount of carbon-14 remaining in an organic material. Synonymous with "carbon-14 age."

rebound. Upward flexing of Earth's crust. Synonymous with "upwarping."

recharge. The addition of water to the saturated zone below the water table.

reflection shooting. A type of seismic survey based on measurement of the travel times of seismic waves that originate from an artificially produced disturbance and are reflected back at near-vertical incidence from subsurface boundaries, resulting in a separation of media of different densities and/or elastic-wave velocities.

regolith. From the Greek "rhegos" (blanket) + "lithos" (stone), the layer of unconsolidated rock material that forms the surface of the land and overlies or covers bedrock; includes rock debris of all kinds, volcanic ash, glacial drift, alluvium, loess, and aeolian deposits, vegetal accumulations, and soil.

regression. Long-term seaward retreat of the shoreline or relative fall of sea level.

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

rift. A region of Earth's crust where extension results in formation of many related normal faults, commonly associated with volcanic activity.

rift valley. A depression formed by grabens along the crest of a mid-ocean ridge or in a continental rift zone.

right-lateral fault. A strike-slip fault on which the side opposite the observer has been displaced to the right.

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

riprap. A layer of large, durable rock fragments placed in an attempt to prevent erosion by water and thus preserve the shape of a surface, slope, or underlying structure.

roche moutonnée. A glacially sculpted, elongated bedrock knob or hillock.

rockfall. The most rapid type of slope movement in which a newly detached fragment of bedrock of any size falls from a cliff or other very steep slope, traveling straight down or in a series of leaps and bounds down a slope.

roundness. The relative amount of curvature of the "corners" of a sediment grain.

sand. A clastic particle smaller than a granule and larger than a silt grain, with a diameter ranging from 1/16 to 2 mm (0.0025 to 0.08 in).

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

saturated zone. A subsurface zone in which all the interstices are filled with water under pressure greater than that of the atmosphere; separated from the unsaturated zone (above) by the water table.

scarp. A steep cliff or topographic step resulting from displacement on a fault or as a result of slope movement or erosion. Synonymous with "escarpment."

scour. The powerful and concentrated clearing and digging action of flowing water, air, or ice.

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

sedimentary. Pertaining to or containing sediment.

sedimentary rock. A rock resulting from the consolidation of loose sediment that has accumulated in layers; it may be "clastic," consisting of mechanically formed fragments of older rock; "chemical," formed by precipitation from solution; or "organic," consisting of the remains of plants and animals. One of the three main classes of rock—igneous, metamorphic, and sedimentary.

sedimentation. The process of forming or accumulating sediment into layers, including the separation of rock particles from parent rock, the transportation of these particles to the site of deposition, the actual deposition or settling of the particles, the chemical and other changes occurring in the sediment, and the ultimate consolidation of the sediment into solid rock.

seiche. An oscillation of a body of water in an enclosed or semi-enclosed basin that varies in period—depending on the physical dimensions of the basin—from a few minutes to several hours, and in height from several centimeters to a few meters; primarily caused by local changes in atmospheric pressure, aided by winds, tidal currents, and earthquakes.

seismic. Pertaining to an earthquake or Earth vibration, including those that are artificially induced.

seismicity. The phenomenon of movements in the Earth's crust. Synonymous with "seismic activity."

sequence. A succession of geologic events, processes, or rocks, arranged in chronologic order to show their relative position and age with respect to geologic history as a whole. Also, a rock-stratigraphic unit that is traceable over large areas and defined by sediment associated with a major sea level transgression–regression.

shale. A clastic sedimentary rock made of clay-sized particles and characterized by fissility.

sheetwash. A sheetflood occurring in a humid region. Also, the material transported and deposited by the water of a sheetwash.

shoal. A relatively shallow place in a stream, lake, sea, or other body of water.

shoaling. To become shallow gradually, to fill up or block off with a shoal, or to proceed from a greater to a lesser depth of water.

shoreface. The zone between the seaward limit of the shore and the more nearly horizontal surface of the offshore zone; typically extends seaward to storm wave depth or about 10 m (30 ft).

silicate. A mineral group composed of silicon (Si) and oxygen (O) plus an element or elements, for example, quartz, SiO_2; olivine, $(Mg, Fe)_2SiO_4$; and pyroxene, $(Mg,Fe)SiO_3$; as well as the amphiboles, micas, and feldspars.

silt. Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay, 0.0039 to 0.063 mm (0.00015 to 0.0025 in) across.

silting. The accumulation of silt suspended throughout a body of standing water or in some considerable portion of it. In particular, the choking, filling, or covering with stream-deposited silt behind a dam or other place of retarded flow, or in a reservoir. Synonymous with "siltation."

siltstone. A clastic sedimentary rock composed of silt-sized grains.

slabbing. Rock splitting into slabs along closely spaced parallel fissures, commonly falling under the force of gravity from a cliff face.

slope. The inclined surface of any part of Earth's surface, such as a hillslope. Also, a broad part of a continent descending into an ocean.

slope movement. The gradual or rapid downslope movement of soil or rock under gravitational stress.

Synonymous with "mass wasting."

slump. A generally large, coherent slope movement with a concave failure surface and subsequent backward rotation relative to the slope.

soil. The unconsolidated portion of the Earth's crust modified through physical, chemical, and biotic processes into a medium capable of supporting plant growth.

sorted. Describes an unconsolidated sediment consisting of particles of essentially uniform size.

sorting. The dynamic process by which sedimentary particles having some particular characteristic (such as similarity of size, shape, or specific gravity) are naturally selected and separated from associated but dissimilar particles by the agents of transportation.

spalling. The process by which scales, plates, or flakes of rock, from less than a centimeter to several meters thick, successively fall from the bare surface of a large rock mass; a form of exfoliation.

speleothem. Any secondary mineral deposit that forms in a cave.

spring. A place where groundwater flows naturally from a rock or the soil onto the land surface or into a body of surface water.

stage. A major subdivision of a glacial epoch, particularly one of the cycles of growth and disappearance of the Pleistocene ice sheets.

stalactite. A conical or cylindrical speleothem that hangs from the ceiling or wall of a cave, deposited from drops of water and usually composed of calcite but may be formed of other minerals.

stalagmite. A conical or cylindrical speleothem that is developed upward from the floor of a cave by the action of dripping water, usually formed of calcite but may be formed of other minerals.

storm surge. An abnormal, sudden rise of sea level along an open coast during a storm, caused primarily by strong winds offshore, or less frequently, a drop in atmospheric pressure, resulting in water piled up against the coast. It is most severe during high tide.

strata. Tabular or sheetlike layers of sedimentary rock that are visually distinctive from other layers above and below. The singular form of the term is stratum, but is less commonly used.

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

stratigraphy. The geologic study of the origin, occurrence, distribution, classification, correlation, and age of rock layers, especially sedimentary rocks.

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

stream channel. A long, narrow depression shaped by the concentrated flow of stream water.

stream terrace. A planar surface alongside a stream valley representing the remnants of an abandoned floodplain, stream bed, or valley floor produced during a former stage of erosion or deposition.

striations (glacial). One of a series of long, delicate, finely cut, commonly straight and parallel furrows or lines inscribed on a bedrock surface by the rasping and rubbing of rock fragments embedded at the base of a moving glacier, usually oriented in the direction of ice movement; also form on the rock fragments transported by a glacier.

strike. The compass direction of the line of intersection of an inclined surface with a horizontal plane.

strike-slip fault. A fault with measurable offset where the relative movement is parallel to the strike of the fault. Described as left-lateral (sinistral) when relative motion of the block opposite the observer is to the left, and right-lateral (dextral) when relative motion is to the right.

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

submergence. A rise of water level in relation to land, so that areas of formerly dry land become inundated; results from either a sinking of the land or rise of water level.

subsidence. The sudden sinking or gradual downward settling of part of Earth's surface.

syncline. A generally concave upward fold of which the core contains the stratigraphically younger rocks.

system (stratigraphy). The fundamental unit of chronostratigraphic classification of Phanerozoic rocks; each unit represents a time span and an episode of Earth history sufficiently great to serve as a worldwide reference unit. It is the temporal equivalent of a period.

tectonic. Describes a feature or process related to large-scale movement and deformation of Earth's crust.

terrace. Any long, narrow, relatively level or gently inclined surface (i.e., a bench or steplike ledge) that is bounded along one edge by a steeper descending slope and along the other edge by a steeper ascending slope, thus breaking the continuity of the slope; commonly occurs along the margin and above the level of a body of water, marking a former water level.

terrestrial. Describes a feature, process, or organism related to land, Earth, or its inhabitants.

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

till. Unstratified drift deposited directly by a glacier without reworking by meltwater and consisting of a mixture of clay, silt, sand, gravel, and boulders ranging widely in size and shape.

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

trace (structural geology). The intersection of a geological surface with another surface, for example, the trace of bedding on a fault surface, or the trace of a fault or outcrop on the ground.

trace fossil. A fossilized feature such as a track, trail, burrow, or coprolite (dung), that preserves evidence of an organism's life activities, rather than the organism itself. Compare to "body fossil."

transform fault. A strike-slip fault that links two other faults or plate boundaries such as two segments of a mid-ocean ridge.

transgression. Landward migration of the sea as a result of a relative rise in sea level.

trend. The direction or bearing of an outcrop of a geologic feature such as an ore body, fold, or orogenic belt.

type locality. The place where a geologic feature such as an ore occurrence, a particular kind of igneous rock, or the type specimen of a fossil species was first recognized and described.

unconfined groundwater. Groundwater that has a water table; water not confined under pressure beneath a confining bed.

unconformable. Describes strata that do not succeed the underlying rocks in immediate order of age or in parallel position, especially younger strata that do not have the same dip and strike as the underlying rocks. Also, describes the contact between unconformable rocks.

unconformity. A substantial break or gap in the geologic record where a rock unit is overlain by another that is not next in stratigraphic succession, resulting from either a change that caused deposition to cease for a considerable span of time or erosion with loss of the previously formed record.

undercutting. The removal of material at the base of a steep slope by the erosive action of water (such as a meandering stream), sand-laden wind in a desert, or waves along a coast.

underfit stream. A stream that appears to be too small to have eroded the valley in which it flows. Also, a stream whose volume is greatly reduced or whose meanders show a pronounced shrinkage in radius.

unsaturated zone. A subsurface zone between the land surface and the water table that includes air, gases, and water held by capillary action. Synonymous with "vadose zone" and "zone of aeration."

uplift. A structurally high area in Earth's crust produced by movement that raises the rocks.

upwarping. Upward flexing of Earth's crust on a regional scale as a result of the removal of ice, water, sediments, or lava flows.

vadose water. Water of the unsaturated zone.

varve. Any cyclic, genetically related paired sedimentary layer, generally occurring in a repeating series, such as seasonally deposited glacial varves, but also laminated nonglacial shale, evaporite, and other sediments.

varve (glacial). A sedimentary layer deposited in a body of still water within one year's time, specifically a thin pair of graded glaciolacustrine layers seasonally deposited, usually by meltwater streams into a glacial lake or other body of still water in front of a glacier.

vent. Any opening at Earth's surface through which magma erupts or volcanic gases are emitted.

volatile. Readily vaporizable.

volcanic. Pertaining to the activities, structures, or rock types of a volcano. A synonym of extrusive.

volcanism. The processes by which magma and its associated gases rise into Earth's crust and are extruded onto the surface and into the atmosphere.

water table. The surface between the saturated zone and the unsaturated zone. Synonymous with "groundwater table" and "water level."

weathering. The physical, chemical, and biological processes by which rock is broken down, particularly at Earth's surface.

wind tide. The part of the tide produced by wind, rather than astronomical forces; specifically the change in water level as a result of wind moving across the surface.

Wisconsinan. Pertaining to the classical fourth glacial stage of the Pleistocene Epoch in North America, following the Sangamonian interglacial stage and preceding the Holocene Epoch.

Literature Cited

This section lists references cited in this report. Contact the Geologic Resources Division for assistance in obtaining these documents.

Anderson, L. 2003. Evaluation of shoreline erosion extent and processes on Wisconsin's Lake Superior shoreline. Thesis. University of Wisconsin, Madison, Wisconsin.

Behrendt, J. C., A. G. Freen, W. F. Cannon, D. R. Hutchinson, M. W. Lee, B. Milkereit, W. F. Agena, and C. Spencer. 1988. Crustal structure of the Midcontinent Rift System: results from GLIMPCE deep seismic reflection profiles. Geology 16:81–85.

Bennett, J. P., and C. M. Wetmore. 2005. Lichens of the U. S. National Parks. The Bryologist 108(4):544–553.

Black, R. F. 1974. Geology of Ice Age National Scientific Reserve of Wisconsin. Scientific Monograph Series Number Two. National Park Service, Washington, DC.

Blewett, W. 2006. Understanding ancient shorelines in the national parks of the Great Lakes; an interpretative guidebook developed as a 'geoscientist-in-the-park' at Michigan's Pictured Rocks National Lakeshore. Geological Society of America Abstracts with Programs 38(7).

Bona, L. J. 1990. Geomorphology and recent geologic history of Long Island Apostle Islands National Lakeshore, Wisconsin. Thesis. University of Wisconsin, Madison, Wisconsin.

Bona, L. J. and D. S. Kiesel. 1990. Geomorphology and Holocene geologic history of Long Island, Apostle Islands National Lakeshore, Wisconsin. Geological Society of America Abstracts with Programs 22(5):4.

Braile, L.W. 2009. Seismic monitoring. Pages 229–244 *in* R. Young, R. and L. Norby, editors. Geological Monitoring. Geological Society of America, Boulder, Colorado. http://nature.nps.gov/geology/monitoring/seismic.cfm (accessed 6 June 2014).

Brown, B. 2006. Building and ornamental stone from the Precambrian rocks of Wisconsin; a review of historic production and future prospects. Geological Society of America Abstracts with Programs 38(4).

Brunner, J., J. Kenworthy, and V. Santucci. 2009. Unauthorized fossil collecting from National Park Service shorelines: Servicewide policy and perspectives. Pages 319-323 *in* S. Weber, editor. Rethinking Protected Areas in a Changing World: Proceedings of the 2009 George Wright Society Biennial Conference on Parks, Protected Areas, and Cultural Sites. The George Wright Society, Hancock, Michigan. http://www.georgewright.org/0956brunner.pdf (accessed 7 January 2015).

Burghardt, J. E., E. S. Norby, and H. S. Pranger, II. 2014. Abandoned mineral lands in the National Park System: comprehensive inventory and assessment. Natural Resource Technical Report NPS/NRSS/GRD/NRTR—2014/906. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/App/Reference/Profile/2192198 (accessed 3 June 2014).

Busch, J. C. 2008. People and places: a human history of the Apostle Islands. Historic resource study of the Apostle Islands National Lakeshore. Midwest Regional Office, National Park Service, Omaha, Nebraska. http://www.nps.gov/apis/historyculture/upload/Historic%20Resource%20Study.pdf (accessed 6 June 2014).

Bush, D. M. 2009. Marine features and processes. Pages 163–188 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://nature.nps.gov/geology/monitoring/marine.cfm (accessed 7 April 2015).

Bush, D. M., and R. Young. 2009. Coastal features and processes. Pages 47–67 *in* R. Young and L. Norby, editors. Geological Monitoring. Geological Society of America, Boulder, Colorado. http://nature.nps.gov/geology/monitoring/coastal.cfm (accessed 6 June 2014).

Caffrey, M. 2007. Visualization lake level fall. Unpublished simulation. Internal document, Geologic Resources Division, National Park Service, Denver, Colorado.

Cannon, W. F. 1994. Closing of the Midcontinent rift—a far-field effect on Grenvillian compression. Geology 22(2):155–158. http://pubs.er.usgs.gov/publication/70017864 (accessed 9 April 2015).

Cannon, W. F., and S. W. Nicholson. 1992. Revisions of stratigraphic nomenclature within the Keweenawan Supergroup of northern Michigan. Pages A1–A8 (chapter A) *in* W. F. Cannon and S. W. Nicholson, editors. Contributions to the geology and mineral resources of the Midcontinent rift system. Bulletin 1970-A, B. US Geological Survey, Reston, Virginia. http://pubs.usgs.gov/bul/1970a-b/report.pdf (accessed 7 April 2015).

Cannon, W. F., L. G. Woodruff, S. W. Nicholson, and C. A. Hedgman. 1996. Bedrock geologic map of the Ashland and the northern part of the Ironwood 30' × 60' quadrangles, Wisconsin and Michigan (scale 1:100,000). Miscellaneous Geologic Investigations Map I-2566. US Geological Survey, Reston, Virginia. http://ngmdb.usgs.gov/Prodesc/proddesc_13052.htm (accessed 15 June 2014).

Cannon, W. F., L. G. Woodruff, S. W. Nicholson, C. A. Hedgman, and R. D. Barber-Delach. 1999. Digital bedrock geologic map of the Ashland and northern part of the Ironwood 30' × 60' quadrangles, Wisconsin and Michigan (scale 1:100,000). Open-File Report OF 99-546. US Geological Survey, Reston Virginia. http://pubs.er.usgs.gov/publication/ofr99546 (accessed 12 May 2014).

Cary, S. J., P. F. McDowell, and L. J. Graumilch. 1979. Soils and surficial geology of four Apostle Islands. Wisconsin Academy of Sciences, Arts and Letters 67:14–30.

Clayton, L. 1984. Pleistocene geology of the Superior region, Wisconsin. Information Circular Number 46. Wisconsin Geological and Natural History Survey, Madison, Wisconsin. http://wisconsingeologicalsurvey.org/pdfs/IC46.pdf (accessed 12 June 2014).

Clayton, L. 1985. Pleistocene geology of the Superior region, Wisconsin (scale 1:250,000). Regional Map Series 3. Wisconsin Geological and Natural History Survey, Madison, Wisconsin.

Climate Change Response Program. 2012. Climate change case study: Apostle Islands National Lakeshore. Unpublished report. National Park Service, Climate Change Response Program, Fort Collins, Colorado.

Coburn, A. S., A. D. Griffith, and R. S. Young. 2010. Inventory of coastal engineering projects in coastal national parks. Natural Resource Technical Report NPS/NRPC/GRD/NRTR—2010/373. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/App/Reference/Profile/2165163 (accessed 20 March 2015).

Culler, R.L., and P. Berendsen. 1998. The provenance and chemical variation of sandstones associated with the Midcontinent rift system, USA. European Journal of Mineralogy 10:987–1002.

Curdts, T. 2011. Shoreline length and water area in the ocean, coastal and Great Lakes parks: updated statistics for shoreline miles and water acres (rev1b). Natural Resource Report NPS/WASO/NRR—2011/464. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/App/Reference/Profile/2180595/ (accessed 26 December 2013).

Davis, D. W., and J. B. Paces. 1990. Time resolution of geologic events on the Keweenaw Peninsula and implications for development of the Midcontinent rift system. Earth and Planetary Science Letters 97:54–64.

Davis, M. B., C. Douglas, and R. Calcote. 1998. Holocene paleoenvironments in the western Great Lakes parks. Pages 10–52 *in* Holocene paleoenvironments in western Great Lakes Parks. Final report to the National Park Service. US Geological Survey, Biological Resources Division, Western Great Lakes Global Change Research Program, University of Missouri, Columbia, Missouri.

Desai, A. R., J. A. Austin, V. Bennington, and G. A. McKinley. 2009. Stronger winds over a large lake in response to weakening air-to-lake temperature gradient. Nature Geoscience Letters 2:855–858. http://www.nature.com/ngeo/journal/v2/n12/full/ngeo693.html (accessed 7 April 2015).

Dott, R. H., and J. W. Attig. 2004. Roadside geology of Wisconsin. Mountain Press Publishing Co., Missoula, Montana.

Eichenlaub, V. L. 1979. Weather and climate of the Great Lakes region. University of Notre Dame Press, Notre Dame, Indiana.

Engstrom, W. N. 1974a. Spatial variations in beach height and width in the Apostle Islands, northern Wisconsin. The Yearbook (Association of Pacific Coast Geographers) 36:146–147.

Engstrom, W. N. 1974b. Beach foreshore sedimentology and morphology in the Apostle Islands of northern Wisconsin. Journal of Sedimentary Petrology 44(1):190–206.

Engstrom, W. N. 1985. Recent beach erosion along spits and cuspate forelands of Apostle Islands National Lake Shore. Shore and Beach 53:22–28.

Farrand, W. R. 1960. Former shorelines in western and northern Lake Superior basin. Dissertation. University of Michigan, Ann Arbor, Michigan.

Gable, D. J., and T. Hatton. 1983. Maps of vertical crustal movements in the conterminous United States over the last 10 million years. Miscellaneous Investigations Series Map MI 1315. US Geological Survey, Reston, Virginia.

Gafvert, U. 2009. Monitoring land cover and land use in Great Lakes Network parks. Unpublished report. National Park Service, Ashland, Wisconsin.

Galston, L. 2008. Re-evaluation of the Proterozoic Devils Island Sandstone, Keweenawan rift, northern Wisconsin. Geological Society of America Abstracts with Programs 40(5):76. https://gsa.confex.com/gsa/2008NC/finalprogram/abstract_138108.htm (accessed 9 April 2015).

Great Lakes Network. 2007. Climate Change, impacts of Midwest warming. Resource brief. National Park Service, Great Lakes Network, Ashland, Wisconsin.

Great Lakes Network. 2009. Climate Change. Resource brief. National Park Service, Great Lakes Network, Ashland, Wisconsin.

Great Lakes Network. 2011a. Monitoring diatoms in lake bottom sediments. Resource brief. National Park Service, Great Lakes Network, Ashland, Wisconsin.

Great Lakes Network. 2011b. Water quality monitoring in the Apostle Islands. Resource brief. National Park Service, Great Lakes Network, Ashland, Wisconsin.

Great Lakes Network. 2012a. Climate monitoring in Great Lakes National Parks. Resource brief. National Park Service, Great Lakes Network, Ashland, Wisconsin.

Great Lakes Network. 2012b. Monitoring landscape dynamics in the Apostle Islands. Resource brief. National Park Service, Great Lakes Network, Ashland, Wisconsin.

Great Lakes Network. 2013. Climate trends at Apostle Islands National Lakeshore. Resource brief. National Park Service, Great Lakes Network, Ashland, Wisconsin.

Hansel, A. K., D. M. Mickelson, A. F. Schneider, and C. E. Larsen. 1985. Late Wisconsinan and Holocene history of the Lake Michigan basin. Pages 39–53 in P. F. Karrow and P. E. Calkin, editors. Quaternary evolution of the Great Lakes. Special Paper 30. Geological Association of Canada, Toronto, Ontario.

Hart, M., and U. Gafvert. 2006. Data management plan: Great Lakes Inventory and Monitoring Network. Document number GLKN/2006/20. National Park Service, Great Lakes Network, Ashland, Wisconsin.

Havholm, K. 2007. Investigator's annual report. Unpublished report. Apostle Islands National Lakeshore, Bayfield, Wisconsin.

Highland, L. M., and P. Bobrowsky. 2008. The landslide handbook—a guide to understanding landslides. Circular 1325. US Geological Survey, Reston, Virginia. http://pubs.usgs.gov/circ/1325/ (accessed 6 June 2014).

Hinze, W. J., D. J. Allen, L. W. Braile, and J. Mariano. 1997. The Midcontinent rift system: a major Proterozoic continental rift. Pages 7–35 *in* R. W. Ojakangas, A. B. Dickas, and J. C. Green, editors. Middle Proterozoic to Cambrian rifting, central North America. Special Paper 312. Geological Society of America, Boulder, Colorado.

Holmes, R. R. Jr., L. M. Jones, J. C. Eidenshink, J. W. Godt, S. H. Kirby, J. J. Love, C. A. Neal, N. G. Plant, M. L. Plunkett, C. S. Weaver, A. Wein, and S. C. Perry. 2013. US Geological Survey natural hazards science strategy—Promoting the safety, security, and economic well-being of the nation. Circular 1383–F. US Geological Survey, Reston, Virginia. http://pubs.usgs.gov/circ/1383f/ (accessed 6 June 2014).

Huff, M. D., and J. Swenson. 2002. Sedimentation in western Lake Superior. Geological Society of America Abstracts with Programs 34(2):12.

Hunt, R. K., J. P. Kenworthy, and V. L. Santucci. 2008. Paleontological resource inventory and monitoring—Great Lakes Network. Natural Resource Technical Report NPS/NRPC/NRTR—2008/120. National Park Service, Fort Collins, Colorado.

Jordahl, H. C., Jr. 1994. A unique collection of islands. The influence of history, politics, policy, and planning on the establishment of the Apostle Islands National Lakeshore. University of Wisconsin, Madison, Wisconsin.

Kraft, G. 1982. Soil and recreational use on the Apostle Islands National Lakeshore: I. Soil suitability for trails and campsites, II. Bank erosion in the Presque Isle campground. Dissertation. University of Wisconsin, Stevens Point, Wisconsin.

LaBerge, G. L. 1994. Geology of the Lake Superior region. Geoscience Press, Phoenix, Arizona.

Lafrançois, T., M. B. Edlund, L. Ferrington Jr., A. Egan, A. Fedie, and J. Glase. 2010. Mapping and biological studies of shoreline rock pools in three Lake Superior national parks (part of GLRI project 90). Summary trip report for 2010 fieldwork in Apostle Islands National Park. Unpublished report. National Park Service.

Lafrançois B. M., S. C. Riley, D. S. Blehert, and A. E. Ballmann. 2011. Links between type E botulism outbreaks, lake levels, and surface water temperatures in Lake Michigan, 1963–2008. Journal of Great Lakes Research 37:86–91.

Lancaster, N. 2009. Aeolian features and processes. Pages 1–25 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://nature.nps.gov/geology/monitoring/aeolian.cfm (accessed 6 June 2014).

Larsen, C. E. 1999. Submergence along the south and western shore of Lake Superior since 2100 yrs B.P. Program and Abstracts of the Conference of the International Association for Great Lakes Research 42:A-66.

Larsen, C. E., C. C. Cameron, and E. I. Robbins. 1999. The reconstructed Late Holocene lake-level history of the Apostles Islands National Lakeshore, Lake Superior. Program and Abstracts of the Conference of the International Association for Great Lakes Research 42:A-66–67.

Lord, M. L., D. Germanoski, and N. E. Allmendinger. 2009. Fluvial geomorphology: Monitoring stream systems in response to a changing environment. Pages 69–103 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://nature.nps.gov/geology/monitoring/fluvial.cfm (accessed 6 June 2014).

Martin, L. 1916. The physical geography of Wisconsin. Bulletin No. XXXVI, Educational Series No. 4. Wisconsin Geological and Natural History Survey, Madison, Wisconsin. http://archive.org/stream/physicalgeograph00martrich/physicalgeograph00martrich_djvu.txt (accessed 12 June 2014).

Melillo, J. M., T. C. Richmond, and G. W. Yohe, editors. 2014. Climate change impacts in the United States: the third national climate assessment. US Global Change Research Program. http://nca2014.globalchange.gov/downloads (accessed 12 August 2014).

Miller, M. Date unknown. Mineral occurrence at Apostle Islands National Lakeshore. Unpublished report. National Park Service, Geologic Resources Division, Denver, Colorado.

Minnesota Sea Grant. 2014. Lake Superior's natural processes. Minnesota Sea Grant, University of Minnesota, Duluth, Minnesota. http://www.seagrant.umn.edu/superior/processes (accessed 21 October 2014).

National Oceanic and Atmospheric Administration. 2014. Water levels of the Great Lakes. National Oceanic and Atmospheric Administration, Ann Arbor, Michigan. http://www.glerl.noaa.gov/pubs/brochures/lakelevels/lakelevels.pdf (accessed 6 November 2014).

National Park Service. 2004. Final wilderness study: Apostle Islands. Apostle Islands National Lakeshore, Bayfield, Wisconsin. http://www.nps.gov/apis/parkmgmt/wild-study.htm (accessed 11 September 2014).

National Park Service. 2005. Geology fieldnotes: Apostle Islands National Lakeshore, Wisconsin. Online information. National Park Service, Geologic Resources Division, Lakewood, Colorado. http://www2.nature.nps.gov/geology/parks/apis/ (accessed 15 June 2014).

National Park Service. 2011. Final General management plan / wilderness management plan / environmental impact statement for Apostle Islands National Lakeshore. Apostle Islands National Lakeshore, Bayfield and Ashland counties, Wisconsin. http://www.nps.gov/apis/learn/management/gmp.htm (accessed 3 April 2015).

Natural Resources Research Institute. 2001. Pre-settlement vegetation. University of Minnesota, The Lake Superior Decision Support Project, Duluth, Minnesota. http://www.nrri.umn.edu/lsgis/fservice.htm (accessed 30 June 2014).

Natural Resources Research Institute. 2006. Important habitat sites and areas in the Lake Superior basin 2006. University of Minnesota, The Lake Superior Decision Support Project, Duluth, Minnesota. http://www.nrri.umn.edu/lsgis/importanthabitat.htm (accessed 30 June 2014).

Nicholson, S. W., W. F. Cannon, L. G. Woodruff, and C. L. Dicken. 2004a. Bedrock geologic map of the Port Wing, Solon Springs, and parts of the Duluth and Sandstone 30' × 60' quadrangles, Wisconsin (scale 1:100,000). Open-File Report 2004-1303. US Geological Survey, Reston, Virginia. http://pubs.er.usgs.gov/publication/ofr20041303 (accessed 12 May 2014).

Nicholson, S. W., C. L. Dicken, M. P. Foose, and J. Mueller. 2004b. Integrated geologic map databases for the United States, the upper Midwest states: Minnesota, Wisconsin, Michigan, Illinois, and Indiana (scale 1:500,000). Open-File Report 2004-1355. US Geological Survey, Reston, Virginia. http://pubs.er.usgs.gov/publication/ofr20041355 (accessed 12 May 2014).

Nicholson, S. W., W. F. Cannon, L. G. Woodruff, and C. L. Dicken. 2006. Bedrock geologic map of the Port Wing, Solon Springs, and parts of the Duluth and Sandstone 30' × 60' quadrangles, Wisconsin and Minnesota (scale 1:100,000). Scientific Investigations Map 2869. US Geological Survey, Reston, Virginia. http://pubs.usgs.gov/sim/2869/report.pdf (accessed 18 August 2014).

Nuhfer, E. B., and M. P. Dalles. 1994. Lake Superior's Apostle Islands National Lakeshore as a resource for geologic education. Geological Society of America Abstracts with Programs 26(5):56.

Nuhfer, E. B., and M. P. Dalles. 2004. A guidebook to the geology of Lake Superior's Apostle Islands National Lakeshore and nearby areas of the Bayfield Peninsula of Wisconsin. Revised edition. Eastern National, Fort Washington, Pennsylvania.

Ojakangas, R. W., D. Cramer, and T. Fitz. 2011. Trip 3—geology of the Bayfield Peninsula: Keweenawan Bayfield Group and Pleistocene deposits. Pages 51–77 in T. Fitz, A. Mills, K. Wilson, C. Bodette, and D. Cramer, editors. Proceedings Volume 57. Institute on Lake Superior Geology, Ashland, Michigan. http://www.d.umn.edu/prc/lakesuperiorgeology/Volumes/ILSG11%20Guidebook-fixed.pdf (accessed 7 April 2015).

Ojakangas, R. W., A. B. Dickas, and J. C. Green. 1997. Introduction: Middle Proterozoic to Cambrian rifting, central North America. Pages 1–6 in Ojakangas, R. W., A. B. Dickas, and J. C. Green, editors. Middle Proterozoic to Cambrian rifting, central North America. Special paper 312. Geological Society of America, Boulder, Colorado.

Pendleton, E. A., E. R. Thieler, and S. J. Williams. 2007. Coastal change-potential assessment of Sleeping Bear Dunes, Indiana Dunes, and Apostle Islands National Lakeshore to lake-level changes. Open-File Report 2005-1249. US Geological Survey, Woods Hole, Massachusetts. http://pubs.usgs.gov/of/2005/1249/index.html (accessed 18 June 2014).

Peterson, W. L. 1986. Late Wisconsinan glacial history of northeastern Wisconsin and western Upper Michigan. Bulletin 1652. US Geological Survey, Reston, Virginia. http://pubs.er.usgs.gov/publication/b1652 (accessed July 4, 2014).

Petersen, M. D., A. D. Frankel, S. C. Harmsen, C. S. Mueller, K. M. Haller, R. L. Wheeler, R. L. Wesson, Y. Zeng, O. S. Boyd, D. M. Perkins, N. Luco, E. H. Field, C. J. Wills, and K. S. Rukstales. 2008. Documentation for the 2008 update of the United States national seismic hazard maps. Open-file report 2008–1128. US Geological Survey, Reston, Virginia. http://pubs.usgs.gov/of/2008/1128/ (accessed 15 January 2014).

Pranger, H. 2005. Recommendations for Disturbed Land Restoration at Ironwood Island, Apostle Islands National Lakeshore, Wisconsin. Unpublished report. National Park Service, Geologic Resources Division, Denver, Colorado.

Robinson, J. E., C. R. Bacon, and C. Wayne. 2012. Under trees and water at Crater Lake National Park, Oregon. Map sheet/poster. Scientific Investigations Map 3223. US Geological Survey, Washington, DC. http://pubs.usgs.gov/sim/3223/ (accessed 1 April 2015).

Rodman, K. 2014. Harsh winter causes greatest Great Lakes ice coverage since 1979. Online article (8 March 2014). Accuweather.com, State College, Pennsylvania. http://www.accuweather.com/en/weather-news/nearly-frozen-lake-superior-ma/23439393 (accessed 1 April 2015).

Rolfhus, K., J. Wiener, M. Sandheinrich, and R. Haro. 2005. Characterization of mercury contamination of aquatic food webs in lagoons in the Apostle Islands National Lakeshore (Lake Superior). Unpublished document. On file at Apostle Islands National Lakeshore, Bayfield, Wisconsin.

Rose, W. J. 1987. Water resources of the Apostle Islands National Lakeshore, northern Wisconsin. Water-Resources Investigations Report 87-4220. US Geological Survey, Madison, Wisconsin. http://pubs.er.usgs.gov/publication/wri874220 (accessed 8 April 2015).

Santucci, V. L., J. P. Kenworthy, and A. L. Mims. 2009. Monitoring in situ paleontological resources. Pages 189–204 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://nature.nps.gov/geology/monitoring/paleo.cfm (accessed 6 June 2014).

Scholz, C. 1984. Late and post-glacial lacustrine sediment distribution in western Lake Superior from seismic reflection profiles. Proceedings and Abstracts for the Annual Institute on Lake Superior Geology 30:61–62.

Stucker, G. 1974. Shores of the Apostles, once again the Manitou treads the land of Hiawatha. National Parks and Conservation Magazine 48(7):4–9.

Swain, A. M., and M. Winkler. 1983. Forest and disturbance history at Apostle Islands National Lakeshore. Park Science 3(4):3–5.

Syverson, K. M., and P. M. Colgan. 2004. The Quaternary of Wisconsin: a review of stratigraphy and glaciation history. Pages 295–311 in J. Ehlers and P. L. Gibbard, editors. Quaternary glaciations—extent and chronology, Part II: North America. Elsevier Publishing, Amsterdam, Netherlands.

Thornberry-Ehrlich, T. L. 2013. Geologic Resources Inventory scoping summary Apostle Islands National Lakeshore. National Park Service, Geologic Resources Division, Denver, Colorado. http://www.nature.nps.gov/geology/inventory/gre_publications.cfm (accessed 12 May 2014).

Thwaites, F. T. 1912. Sandstones of the Wisconsin coast of Lake Superior. Bulletin 25, Scientific Series 8. Wisconsin Geological and Natural History Survey, Madison, Wisconsin.

Toomey, R. S. III. 2009. Geological monitoring of caves and associated landscapes. Pages 27–46 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://nature.nps.gov/geology/monitoring/cavekarst.cfm (accessed 6 June 2014).

Tynan, T. 2012. The bayous of the north: the Kakagon and Bad River sloughs. Online article and video (posting date unknown). http://vimeo.com/32147202 (accessed 11 August 2013).

US Global Change Research Program. 2000. US National assessment of the potential consequences of climate variability and change. US Climate Change Science Program/US Global Change Research Program, Washington, DC.

Varnes, D. J. 1978. Slope movement types and processes. Pages 11–33 *in* R. L. Schuster and R. J. Krizek, editors. Landslides: analysis and control. Special Report 176. National Academy of Science, Transportation and Road Research Board, Washington, DC.

Volkert, R. A., and A. A. Drake Jr. 1999. Geochemistry and stratigraphic relations of middle Proterozoic rocks of the New Jersey Highlands. Professional Paper 1565-C. US Geological Survey, Reston, Virginia. http://pubs.er.usgs.gov/publication/pp1565C (accessed 4 September 2013).

Wieczorek, G. F., and J. B. Snyder. 2009. Monitoring slope movements. Pages 245–271 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://nature.nps.gov/geology/monitoring/slopes.cfm (accessed 6 June 2014).

Wilson, L. R. 1935. The Nipissing flora of the Apostle Islands region. Bulletin of the Torrey Botanical Club 62(9)533–535.

Wright, M. 1997. Apostle Islands National Lakeshore: sea caves. Site bulletin. Geoscientists-in-the-Parks document 1997-APIS. National Park Service, Denver, Colorado.

Wyckoff, J. 1999. Reading the Earth—landforms in the making. Adastra West, Inc. Mahwah, New Jersey.

Young, R. and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado. http://nature.nps.gov/geology/monitoring/index.cfm (accessed 7 April 2015).

Additional References

This section lists additional references, resources, and websites that may be of use to resource managers. Web addresses are valid as of May 2015. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.

Geology of National Park Service Areas

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

NPS Resource Management Guidance and Documents

- 1998 National parks omnibus management act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf
- Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html
- NPS-75: Natural resource inventory and monitoring guideline: http://www.nature.nps.gov/nps75/nps75.pdf
- NPS Natural resource management reference manual #77: http://www.nature.nps.gov/Rm77/
- Geologic monitoring manual (Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado): http://nature.nps.gov/geology/monitoring/index.cfm
- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://www.nps.gov/dsc/technicalinfocenter.htm

Climate Change Resources

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

Geological Surveys and Societies

- Wisconsin Geological and Natural History Survey: http://wgnhs.uwex.edu/
- US Geological Survey: http://www.usgs.gov/
- Geological Society of America: http://www.geosociety.org/
- American Geophysical Union: http://sites.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: http://www.stategeologists.org/

US Geological Survey Reference Tools

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

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting for Apostle Islands National Lakeshore, held on 20-21 July 2010, or the follow-up report writing conference call, held on 19 June 2014. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://go.nps.gov/gripubs.

2010 Scoping Meeting Participants

Name	Affiliation	Position
Peggy Burkman	NPS Apostle Islands National Lakeshore	Biologist
Eric Carson	Wisconsin Geological and Natural History Survey	Geologist
Jim Chappell	Colorado State University	Geologist
Ulf Gafvert	NPS Great Lakes Network	GIS Specialist
Bruce Heise	NPS Geologic Resources Division	Geologist
Jason Kenworthy	NPS Geologic Resources Division	Geologist, GRI reports coordinator
Richard Ojakangas	University of Minnesota (Duluth)	Geologist
Jamie Robertson	Wisconsin Geological and Natural History Survey	Geologist
Brandon Seitz	NPS Grand Portage National Monument	Biological science technician
Trista Thornberry-Ehrlich	Colorado State University	Geologist, GRI report author
Julie Van Stappen	NPS Apostle Islands National Lakeshore	Chief, Planning and Resource Management
Laurel Woodruff	US Geological Survey	Geologist

2014 Conference Call Participants

Name	Affiliation	Position
Peggy Burkman	NPS Apostle Islands National Lakeshore	Biologist
Jim Chappell	Colorado State University	Geologist
Ulf Gafvert	NPS Great Lakes Network	GIS Specialist
Jason Kenworthy	NPS Geologic Resources Division	Geologist, GRI reports coordinator
Dale Pate	NPS Geologic Resources Division	Cave and Karst Program coordinator
Hal Pranger	NPS Geologic Resources Division	Chief, Geologic Features and Systems Branch
Trista Thornberry-Ehrlich	Colorado State University	Geologist, GRI report author
Julie Van Stappen	NPS Apostle Islands National Lakeshore	Chief, Planning and Resource Management
Laurel Woodruff	US Geological Survey	Geologist

Appendix B: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to National Park Service minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of May 2015. Contact the NPS Geologic Resources Division for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester. **National Parks Omnibus Management Act of 1998, 16 USC § 5937** protects the confidentiality of the nature and specific location of cave and karst resources. **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be cancelled with appropriate compensation; and lands are withdrawn from mineral entry.	**36 CFR § 2.1** prohibits possessing/destroying/disturbing…cave resources…in park units. **43 CFR Part 37** states that all NPS caves are "significant" and sets forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.
Paleontology	**National Parks Omnibus Management Act of 1998, 16 USC § 5937** 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. Regulations in association with 2009 PRPA are being finalized (May 2015).	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.

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

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Coastal Features and Processes	**NPS Organic Act, 16 USC § 1 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.

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.

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).

NPS 633/128695, May 2015

National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science
1201 Oak Ridge Drive, Suite 150
Fort Collins, Colorado 80525

www.nature.nps.gov

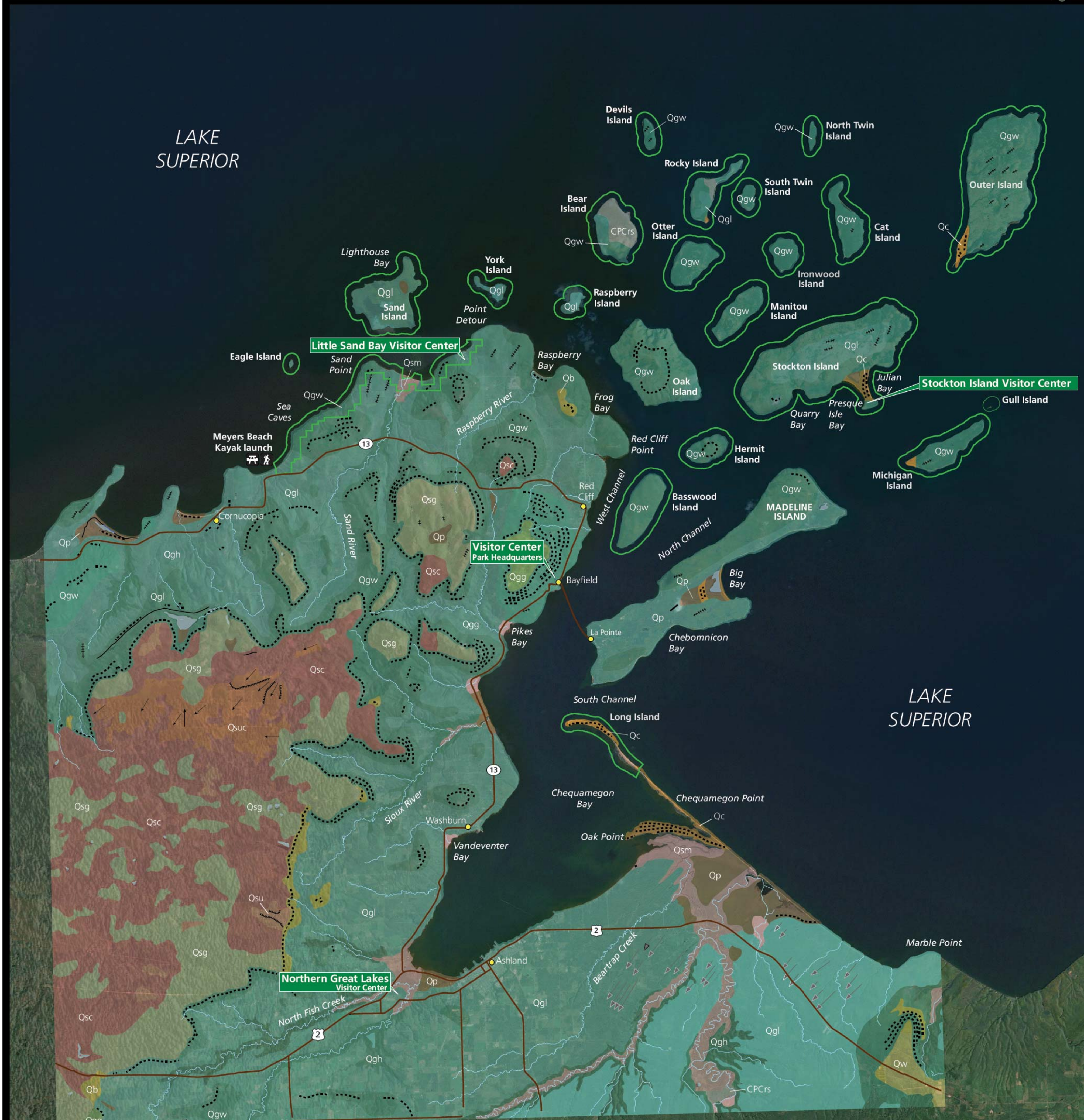
Figure 1. Map of Apostle Islands National Lakeshore. The Apostle Islands extend offshore of the Bayfield Peninsula into Lake Superior in northern Wisconsin. National Park Service map available at http://www.nps.gov/hfc/carto/PDF/APISmap1.pdf (accessed 12 June 2014).

Pleistocene Geologic Map of Apostle Islands NL

Wisconsin

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory



NPS Boundary

Water Bodies

rivers

water

Infrastructure

city

road

Geologic Line Features

abandoned beach and wave-cut bluff

river channel cutback

Glacially Derived Features

direction of glacial stream flow

long axis of drumlin, known or certain

glacial ridge, known or certain

glacial ridge, water or shoreline

long axis of drumlin, direction of glacial ice movement indicated, known or certain

Geologic Units

Qc	Postglacial deposits, shoreline sediment (Holocene)
Qw	Miller Creek Formation, windblown sediment (Holocene)
Qb	Miller Creek Formation, shoreline sediment, offshore sediment (Holocene and Pleistocene)
Qgh	Miller Creek Formation, till - valley sides (Holocene and Pleistocene)
Qgl	Miller Creek Formation, till - lake-modified glacial topography (Holocene and Pleistocene)
Qgw	Miller Creek Formation, till - wave-planed topography (Holocene and Pleistocene)
Qou	Miller Creek Formation, uncollapsed offshore sediment (Holocene and Pleistocene)
Qp	Postglacial deposits, organic sediment (Holocene and Pleistocene)
Qsm	Postglacial deposits, stream sediment (Holocene and Pleistocene)
Qsc	Copper Falls Formation, collapsed proglacial stream sediment (Pleistocene)
Qsg	Copper Falls Formation, hummocky stream sediment overlain by silty material (Pleistocene)
Qsu	Copper Falls Formation, uncollapsed proglacial stream sediment (Pleistocene)
Qsuc	Copper Falls Formation, uncollapsed proglacial stream sediment - Valhalla surface (Pleistocene)
Qgg	Copper Falls Formation, till - thick mass-movement deposits (Pleistocene)
CPCrs	Bedrock (Cambrian or Mesoproterozoic to Neoproterozoic)

North

0 4 8 Kilometers

0 4 8 Miles

This map was produced by Kari Lanphier (Colorado State University) in June 2015. It is an overview of compiled geologic data prepared as part of the NPS Geologic Resources Inventory. This map is not a substitute for site-specific investigations.

The source map used in creation of the digital geologic data was:

Clayton, Lee. 1985. Pleistocene Geology of the Superior Region, Wisconsin (scale 1:250,000). Regional Map Series 3. Wisconsin Geological and Natural History Survey.

As per source map scale and U.S. National Map Accuracy Standards, geologic features represented here are within 127 m (417 ft) of their true location.

All digital geologic data and publications prepared as part of the Geologic Resources Inventory are available at the NPS Integrated Resource Management Applications Portal (IRMA): https://irma.nps.gov/App/Reference/Search. Enter "GRI" as the search text and select a park from the unit list.

Geologic Map of Apostle Islands NL

Wisconsin

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory

North

0 4 8 Kilometers

0 4 8 Miles

NPS Boundary

Water Bodies
- rivers
- water

Infrastructure
- city
- roads

Mine Point Features
- drill hole

Faults
- thrust fault, known or certain
- unknown offset/displacement, known or certain

Geologic Contacts
- known or certain
- water or shoreline
- quadrangle boundary

Outcrop

Geologic Units
- PCch Chequamegon Sandstone (Mesoproterozoic)
- PCdi Devils Island Sandstone (Mesoproterozoic)
- PCo Orienta Sandstone (Mesoproterozoic)
- PCf Freda Sandstone (Mesoproterozoic)

This map was produced by Kari Lanphier (Colorado State University) in June 2015. It is an overview of compiled geologic data prepared as part of the NPS Geologic Resources Inventory. This map is not a substitute for site-specific investigations.

The source maps used in creation of the digital geologic data was:

Cannon, W. F., L. G. Woodruff, S. W. Nicholson, C. A. Hedgman, and R. D. Barber-Delach. 1999. Digital bedrock geologic map of the Ashland and northern part of the Ironwood 30' x 60' quadrangles, Wisconsin, and Michigan. 1:100,000 scale. Open-File Report OF-99-546. US Geological Survey, Reston, Virginia.

Nicholson, S. W., W. F. Cannon, L. G. Woodruff, and C. L. Dicken. 2004. Bedrock geologic map of the Port Wing, Solon Springs, and parts of the Duluth and Sandstone 30' x 60' quadrangles, Wisconsin. 1:100,000 scale. Open-File Report OF-2004-1303. US Geological Survey, Reston, Virginia.

Nicholson, S. W., C. L. Dicken, M. P. Foose, and J. Mueller. 2004. Integrated geologic map databases for the United States, the upper Midwest states: Minnesota, Wisconsin, Michigan, Illinois, and Indiana. 1:500,000 scale. Open-File Report OF-2004-1355. US Geological Survey, Reston, Virginia.

Clayton, L. 1985. Pleistocene geology of the Superior Region, Wisconsin. 1:250,000 scale. Regional Map Series 3.Wisconsin Geological and Natural History Survey, Madison, Wisconsin.

As per source map scale and U.S. National Map Accuracy Standards, geologic features represented here are within 50 m (166 ft) (1:100,000 scale) or 254 m (833 ft) (1:500,000 scale) of their true location.

All digital geologic data and publications prepared as part of the Geologic Resources Inventory are available at the NPS Integrated Resource Management Applications Portal (IRMA): https://irma.nps.gov/App/Reference/Search. Enter "GRI" as the search text and select a park from the unit list.

Surficial ("Pleistocene") Geologic Map Unit Properties Table: Apostle Islands National Lakeshore

Map unit colors correspond to GRI map poster (in pocket). Bold text refers to sections in report.

Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY (Holocene)	Postglacial deposits, shoreline sediment (**Qc**)	**Qc** consists of well-sorted sand and gravel. **Qc** occurs along the shoreline of Lake Superior and no more than a few meters above the present lake level. Long Island is composed entirely of **Qc**. **Qc** is also mapped on Rocky, Outer, Michigan, and Stockton islands.	**Sandscapes**—**Qc** is the primary unit composing the dynamic sandscapes within the lakeshore. **Recent Surficial Deposits**—**Qc** is still collecting and being reworked on the shores of the Apostle Islands by coastal processes. **Sedimentary Rock Features**—modern features in **Qc** such as ripple marks reflect the ancient features in solidified bedrock of the Bayfield Group (**PCdi**, **PCch**, and **PCo**).	**Shoreline Response to Lake-Level Change**—**Qc** is vulnerable to considerable erosion. Sandscapes would decline with rising lake levels. High water caused loss of beach area at Outer Island in spring 2014.	**66 Million Years Ago to Present (Cenozoic Era)—Erosion, Ice Age Glaciation, and Rebound**—**Qc** reflects the ongoing processes of weathering and erosion along the shores of Lake Superior. **Qc** was deposited after about 5,000 years ago.
	Miller Creek Formation, windblown sediment (**Qw**)	**Qw** consists of well-sorted sand. Deposits of **Qw** can reach several meters thick. When enough sand is present, transverse dunes with northward-sloping slip faces form locally. **Qw** is not mapped within Apostle Islands National Lakeshore.	**Aeolian Processes—Qw** forms as wind transports away the finer-grained components. Individual sand grains move via saltation (series of little hops) in the wind.	**Shoreline Response to Lake-Level Change**—**Qw**, where present along the shoreline, is prone to erosion when lake levels drop.	**66 Million Years Ago to Present (Cenozoic Era)—Erosion, Ice Age Glaciation, and Rebound**—**Qw** reflects the ongoing processes of weathering and erosion along the shores of Lake Superior. **Qw** was deposited after about 9,500 years ago following the final retreat of glaciers from the Lake Superior basin and prior to significant vegetation.
QUATERNARY (Holocene and Pleistocene)	Miller Creek Formation, shoreline sediment, offshore sediment (**Qb**)	**Qb** consists of well-sorted sand and gravel in deposits between 1 and 10 m (3 and 30 ft) thick. **Ob** appears as a series of beach ridges (i.e., lines in the GRI GIS geologic map data). **Qb** is not mapped within Apostle Islands National Lakeshore.	**Glacial Features**—**Qb** is well-sorted beach material that collected on the shores of a series of proglacial lakes.	None reported.	**66 Million Years Ago to Present (Cenozoic Era)—Erosion, Ice Age Glaciation, and Rebound**—**Qb** was deposited between about 11,500 and 9,500 years ago as beach deposits on a series of proglacial lakes. **Qb** was deposited after about 9,500 years ago following the final retreat of glaciers from the Lake Superior basin and prior to significant vegetation.

Map unit colors correspond to GRI map poster (in pocket). Bold text refers to sections in report.

Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY (Holocene and Pleistocene)	Miller Creek Formation, till—valley sides (**Qgh**) Miller Creek Formation, till—lake-modified glacial topography (**Qgl**) Miller Creek Formation, till—wave-planed topography (**Qgw**)	Till is unsorted clay, silt, sand, gravel, and boulders (glacial sediment) deposited directly from glacial ice. In general, the Miller Creek Formation is redder in color and richer in clay content than the Copper Falls Formation. **Qgh** is mapped where steep slopes (10° to 15°) cut into the Miller Creek till. Deposits of **Qgl** are of low relief with some hummocky and collapsed (soft-sediment deformation) areas. **Qgl** is commonly 1 to 20 m (3 to 6 ft) thick. **Qgw** occurs on higher and steeper part of the Superior lowland than **Qgl** and was subjected to less wave energy. In less-eroded areas, 1 m (3 ft) of nearshore sand overlies **Qgw**. **Qgl** and **Qgw** are the primary surficial geologic units mapped within Apostle Islands National Lakeshore.	**Glacial Features**—in areas where broad hillsides are exposed as **Qgh**, Miller Creek till, offshore and stream sediment, and Copper Falls till are visible. The hummocky topography of **Qgl** was subdued by wave action, or by being deposited in water-saturated conditions with soft-sediment collapse. Drumlins are mapped in **Qgl**. **Slope Movements—Qgh** features slope wash and slope-movement deposits at the base of hillslopes. Landslides are common.	**Shoreline Response to Lake-Level Change**—**Qgl** and **Qgw** weather to provide sediment to the sandscapes within Apostle Islands National Lakeshore. **Slope Movement Hazards and Risks—Qgl**, **Qgh**, and **Qgw** are prone to slope wash and landslides.	**66 Million Years Ago to Present (Cenozoic Era)—Erosion, Ice Age Glaciation, and Rebound**—**Qgh**, **Qgl**, and **Qgw** were deposited between about 11,500 and 9,500 years ago. Wave action from Lake Superior modified **Qgl**.
	Miller Creek Formation, uncollapsed offshore sediment (**Qou**)	**Qou** consists of finer-grained, offshore sediments with horizontal bedding. **Qou** exhibits flat topography. **Qou** is not mapped within Apostle Islands National Lakeshore.	**Fluvial Features**—the Sand River valley cuts through **Qou** on its course to Lake Superior. **Glacial Features**—**Qou** was deposited on solid ground and was not subject to soft sediment deformation caused by collapse of any underlying ice melting.	**Slope Movement Hazards and Risks—Qou**, as part of the Miller Creek Formation, is prone to slope wash and landslides.	**66 Million Years Ago to Present (Cenozoic Era)—Erosion, Ice Age Glaciation, and Rebound**—**Qou** was deposited between about 11,500 and 9,500 years ago.
	Postglacial deposits, organic sediment (**Qp**)	**Qp** consists of peat or mixtures of organic deposits and fine-grained material in layers between less than 1 m (3 ft) and a few meters thick. Bedding is typically flat. **Qp** is mapped on Sand and Stockton islands.	**Recent Surficial Deposits**—**Qp** accumulated in low-lying swamps, bogs, and marshes. **Paleontological Resources**—**Qp** may contain fossil pollen recording conditions since the last major glaciation of the Pleistocene Epoch.	None reported.	**66 Million Years Ago to Present (Cenozoic Era)—Erosion, Ice Age Glaciation, and Rebound**—**Qp** accumulated in marsh areas since about 10,000 years ago.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY (Holocene and Pleistocene)	Postglacial deposits, stream sediment (**Qsm**)	**Qsm** consists of sand and gravel in overlapping channel deposits (i.e., trough-shaped deposits in cross section). Most deposits of **Qsm** are more than 1 m (3 ft) thick and may be overlain by silt and clay that were overbank deposits. This pattern is typical of meandering streams and adjacent floodplains. **Qsm** is mapped along the shoreline of the mainland unit of Apostle Islands National Lakeshore at the mouth of the Sand River.	**Fluvial Features**—**Qsm** is being deposited at the mouth of the Sand River. Deposits compose terraces and floodplains along the active channel. **Recent Surficial Deposits**—**Qsm** still accumulates in the channels and adjacent floodplains of modern streams.	**Fluvial and Other Surface Water Issues**—**Qsm** is deposited by the Sand River within Apostle Islands National Lakeshore. **Qsm** is unconsolidated and prone to erosion as the river meanders across its floodplain.	**66 Million Years Ago to Present (Cenozoic Era)—Erosion, Ice Age Glaciation, and Rebound**—**Qsm** has accumulated in stream channels and floodplains since about 10,000 years ago.
QUATERNARY (Pleistocene)	Copper Falls Formation, collapsed proglacial stream sediment (**Qsc**) Copper Falls Formation, hummocky stream sediment overlain by silty material (**Qsg**) Copper Falls Formation, uncollapsed proglacial stream sediment (**Qsu**) Copper Falls Formation, uncollapsed proglacial stream sediment—Valhalla surface (**Qsuc**)	**Qsc** formed as mixed stream sediments deposited atop glacial ice. As the ice melted, the sediments collapsed, resulting in faulted bedding and hummocky collapse topography. Surface boulders are rare in **Qsc**. **Qsg** is collapsed stream sediments mixed with till or windblown or offshore sediments and underlying stream sediments. Surface boulders are common in **Qsg**. **Qsu** and **Qsuc** consist of poorly sorted, coarse sediments with undisturbed bedding surfaces. **Qsu** and **Qsuc** exhibit flat topography and no surface boulders. None of these units is mapped within Apostle Islands National Lakeshore.	**Glacial Features**—**Qsc** was deposited on stagnant ice and collapsed when the underlying ice melted. Proglacial streams deposited **Qsg**. **Qsu** and **Qsuc** were deposited on solid ground and were not subject to soft sediment deformation or collapse.	None reported	**66 Million Years Ago to Present (Cenozoic Era)—Erosion, Ice Age Glaciation, and Rebound**—**Qsc**, **Qsg**, **Qsu**, and **Qsuc** were deposited between about 16,000 and 11,500 years ago. Several stability surfaces are present as part of **Qsu**: Lost Lake, Iron River, Valhalla, Lake Ruth, Airport, Swiss, Hayward, and Tiger Cat surfaces.
	Copper Falls Formation, till – thick mass-movement deposits (**Qgg**)	Different types of tills reflect the method of their deposition. Lodgement till is deposited by plastering of glacial debris from the sliding glacial ice. Mass-movement tills are tills that were subject to slope movements after initial deposition. Melt-out tills are released by the melting of stagnant or slowly moving ice without subsequent sedimentary transport or soft-sediment deformation. **Qgg** occurs as mass-movement till, some melt-out till, and lodgement till that covers and obscures older till deposits. In general, the Copper Falls Formation is reddish to brownish sandy sediment. Topography of **Qgg** is hummocky with abundant surface boulders. **Qgg** is not mapped within Apostle Islands National Lakeshore.	**Glacial Features**—**Qgg** displays hummocky topography and three different types of glacial till.	None reported	**66 Million Years Ago to Present (Cenozoic Era)—Erosion, Ice Age Glaciation, and Rebound**—**Qgg** was deposited between about 16,000 and 11,500 years ago.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
CAMBRIAN–PROTEROZOIC	Bedrock (**CPCrs**)	**CPCrs** includes sandstone, mudstone, and conglomerate of **PCch**, **PCdi**, **PCo**, and **PCf** (see Bedrock Geologic Map Unit Properties Table). **CPCrs** is mapped at Bear and Rocky islands.	See Bedrock Geologic Map Unit Properties Table.	See Bedrock Geologic Map Unit Properties Table.	See Bedrock Geologic Map Unit Properties Table.

Bedrock Geologic Map Unit Properties Table: Apostle Islands National Lakeshore

Map unit colors correspond to GRI map poster (in pocket). Bold text refers to sections in report.

Age			Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
MESOPROTEROZOIC ERA	Keweenawan Supergroup	Bayfield Group	Chequamegon Sandstone (**PCch**)	Arkose is a feldspar-rich sandstone. **PCch** contains red, brown, and white arkosic sandstone. Scant beds of red shale and conglomerate occur locally. Feldspar grains are common. Sedimentary bedding is generally thick. **PCch** is about 150 m (490 ft) thick. **PCch** dominates the bedrock within the park, and is mapped on all islands except Eagle, Sand, and Devils.	**Sedimentary Rock Features**—**PCch** contains planar crossbedding, thin channel cross sections, scour-and-fill structures, mud cracks, ripple marks, convoluted bedding and other features associated with braided-stream deposition. Arkose typically forms as a result of granitic rocks breaking down. The presence of large fragments and feldspar commonly means the sediments did not travel far from their point of origin and/or were deposited rapidly because feldspars typically decompose faster than quartz.	**Slope Movement Hazards and Risks—PCch**, as part of the bedrock that composes the cliff shorelines at the lakeshore, is prone to erosion and blockfall. **Caves and Associated Landscape Management**—**PCch** contains sea caves. Climbing in sea caves is restricted at Apostle Island National Lakeshore. **Abandoned Mineral Lands** and **Disturbed Land Restoration**—Brownstones of **PCch** were quarried on three islands at four sites and are now interpretive targets.	**1.6 Billion to 1.0 Billion Years Ago (Mesoproterozic Era)—Continental Rifting, Volcanism, and Sandstone Deposition**—**PCch**, **PCdi**, **PCo, and PCf** were deposited in one of the world's great continental rifts. **PCch** is the youngest member of the Bayfield Group deposited atop **PCdi** in a series of braided streams after the local basin subsided again. The sediment was derived from weathering granites along the flanks of the Midcontinent rift.
			Devils Island Sandstone (**PCdi**)	**PCdi** consists of white to tan quartz sandstone arenite (consolidated sedimentary rock composed of sand-sized fragments). Individual beds within **PCdi** are generally thin. **PCdi** is about 100 m (330 ft) thick. **PCdi** crops out at Devils and Sand islands, and along the shoreline in the mainland unit of Apostle Islands National Lakeshore.	**Sedimentary Rock Features**—**PCdi** contains cross-bedding and ripple marks. **PCdi** is also well sorted. **Devils Island Sandstone Type Locality**—the remarkable exposures of **PCdi** at Devils Island are the geologic type locality. **Paleontological Resources**—**PCdi** contains potential trace fossils as burrows. Microbial fossils are known from rocks similar in age, elsewhere in the region.	**Slope Movement Hazards and Risks—PCdi**, as part of the bedrock that composes the cliff shorelines at Apostle Islands National Lakeshore, is prone to erosion and blockfall. **Caves and Associated Landscape Management**—**PCdi** contains sea caves. Climbing in sea caves is restricted at Apostle Island National Lakeshore. **Paleontological Resource Inventory, Monitoring, and Protection**—If fossils are identified from **PCdi**, they should be documented and an appropriate monitoring protocol established.	**1.6 Billion to 1.0 Billion Years Ago (Mesoproterozic Era)—Continental Rifting, Volcanism, and Sandstone Deposition**—**PCch**, **PCdi**, **PCo, and PCf** were deposited in one of the world's great continental rifts. **PCdi** is the thin, middle member of the Bayfield Group deposited atop **PCo** as a blanket of beach sand flanking numerous shallow ponds and lakes after the basin was partially filled with sediment.
			Orienta Sandstone (**PCo**)	Arkose is a feldspar-rich sandstone. **PCo** is red, brown, and white, arkosic sandstone. Scant beds of red shale and conglomerate occur locally. Feldspar grains are common. **PCo** is approximately 1,000 m (3,300 ft) thick. **PCo** is mapped at Eagle and Sand islands.	**Sedimentary Rock Features**—**PCo** contains planar crossbedding, thin channel cross sections, scour-and-fill structures, mudcracks, ripple marks, convoluted bedding and other features associated with braided-stream deposition. **PCo** is also poorly sorted. Arkose typically forms as a result of granitic rocks breaking down. The presence of large fragments, poor sorting, and feldspar commonly means the sediments did not travel far from their point of origin and/or were deposited rapidly because feldspars typically decompose faster than resistant quartz.	**Slope Movement Hazards and Risks—PCo**, as part of the bedrock that composes the cliff shorelines at the lakeshore, is prone to erosion and blockfall. **Caves and Associated Landscape Management**—**PCo** contains sea caves. Climbing in sea caves is restricted at Apostle Island National Lakeshore.	**1.6 Billion to 1.0 Billion Years Ago (Mesoproterozic Era)—Continental Rifting, Volcanism, and Sandstone Deposition**—**PCch**, **PCdi**, **PCo,** and **PCf** were deposited in one of the world's great continental rifts. **PCo** is the oldest member of the Bayfield Group deposited atop **PCf** in a series of braided streams. The sediment was derived from weathering granites along the flanks of the Midcontinent rift.
		Oronto Group	Freda Sandstone (**PCf**)	**PCf** contains fine- to medium-grained, red, brown, and tan sandstone arenite (consolidated sedimentary rock composed of sand-sized fragments) with lesser shale and conglomerate layers. Feldspar and mica flakes are common. Bedding is well defined. **PCf** is not mapped within Apostle Islands National Lakeshore.	**Sedimentary Rock Features**—**PCf** contains cross-bedding.	None reported.	**1.6 Billion to 1.0 Billion Years Ago (Mesoproterozic Era)—Continental Rifting, Volcanism, and Sandstone Deposition**—**PCch**, **PCdi**, **PCo, and PCf** were deposited in one of the world's great continental rifts. **PCf** is the youngest member of the Oronto Group to form from eroding volcanic rocks of the Keweenawan volcanics.