National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Pipestone National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2017/1512

George Catlin wrote of his journey to Pipestone: "For many miles we had the Coteau in view in the distance before us, which looked like a blue cloud settling down in the horizon . . . On the very top of this mound or ridge, we found the far-famed quarry or fountain of the Red Pipe, which is truly an anomaly in nature. The principal and most striking feature of this place, is a perpendicular wall of close-grained, compact quartz, of twenty-five and thirty feet in elevation, running nearly North and South with its face to the West, exhibiting a front of nearly two miles in length, when it disappears at both ends by running under the prairie . . . At the base of this wall there is a level prairie, of half a mile in width, running parallel to it; in any and all parts of which, the Indians procure the red stone for their pipes, by digging through the soil and several slaty layers of the red stone, to the depth of four or five feet. From the very numerous marks of ancient and modern diggings or excavations, it would appear that this place has been for many centuries resorted to for the red stone; and from the great number of graves and remains of ancient fortifications in its vicinity, it would seem, as well as from their actual traditions, that the Indian tribes have long held this place in high superstitious estimation; and also that it has been the resort of different tribes, who have made their regular pilgrimages here to renew their pipes." (Quote from the Smithsonian website below, citing Truettner 1979 and Gurney and Heyman 2002)

ON THE COVER

George Catlin's 1836 painting *Pipestone Quarry on the Coteau des Prairies*. Courtesy of the Smithsonian American Art Museum, Renwick Gallery, Smithsonian American Art Museum

Gift of Mrs. Joseph Harrison, Jr.

1985.66.337 http://americanart.si.edu/collections/search/artwork/?id=4319.

THIS PAGE

Photograph of a modern quarry in Pipestone National Monument. National Park Service photograph available online: http://www.nps.gov/media/photo/gallery.htm?id=F7D55D62-155D-4519-3E1DF0A992F7F295

Pipestone National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2017/1512

John P. Graham

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

September 2017

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

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

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

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

Views, statements, findings, conclusions, recommendations, and data in this report do not necessarily reflect views and policies of the National Park Service, U.S. Department of the Interior. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the U.S. Government.

This report is available from the Geologic Resources Inventory website, and the Natural Resource Publications Management website. To receive this report in a format optimized for screen readers, please email irma@nps.gov.

Please cite this publication as:

Graham, J. P. 2017. Pipestone National Monument: Geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2017/1512. National Park Service, Fort Collins, Colorado.

NPS 372/140095, September 2017

Contents

Figures

Page

Tables

Page

Executive Summary

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

This report synthesizes discussions from a scoping meeting held in 2008 and a follow-up conference call in 2016 (see Appendix A). Chapters of this report discuss the geologic setting, distinctive geologic features and processes within Pipestone National Monument, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the previously completed GRI map data. A poster (in pocket) illustrates these data.

Pipestone National Monument was established by Congress in 1937 to protect the historic pipestone quarries, considered sacred by many American Indians. Because of its cultural importance, archeological resources, and the Three Maidens petroglyphs, Pipestone National Monument was listed in the National Register of Historic Places in 1966. The monument's 122 ha (301 ac) includes a north–south-trending ridge of Sioux Quartzite and a grassland landscape that includes a restored tallgrass prairie. Thin layers of soft red catlinite, or pipestone, are interbedded with the very hard, fractured Sioux Quartzite.

Lacking quartz, catlinite can be easily carved into pipes and other objects. From 1,000 BCE to 700 CE, prehistoric inhabitants of the Great Plains traded pipestone to people living as far away as what is now Ohio, Kansas, and central North Dakota. The Yankton Sioux eventually controlled the quarries, and in 1858 The Treaty With The Yankton Sioux gave them unrestricted access to the pipestone. Forced onto a reservation 240 km (150 mi) to the west, the Yankton Sioux sold their claim in 1928 to the federal government. When Pipestone National Monument was established, quarrying rights were restored to the Indians.

The 2008 *Final General Management Plan* for Pipestone National Monument emphasizes the setting, site history, and spiritual significance of the national monument as a source of pipestone. The plan recommends eventually relocating the visitor center, other buildings, and the entry road, and restoring the landscape so that it appears as it did in prehistoric times.

Geologic features and processes in Pipestone National Monument include the following:

- Catlinite. Pipestone National Monument preserves the only recognized location of catlinite, the metamorphosed mudstone prized by American Indians for carving calumet pipes, the elbow-shaped and disk-shaped types of pipe commonly used in ceremonies and rituals.
- Fluvial (river) features and processes. Alluvium has accumulated in Pipestone Creek and its floodplain. Winnewissa Falls, a fluvial geomorphic feature characteristic of a change in stream gradient, cascades over the cliff of Sioux Quartzite.
- Eolian (wind) features and processes. Glacial erosion produced fine particles of clay and silt that were transported by wind throughout the region. This windblown silt is called loess.
- Glacial features and processes. Till, a heterogeneous mixture of clay, silt, sand, and gravel deposited during the Pleistocene ice ages, forms the oldest unconsolidated unit in the monument. Glaciers transported boulders from an unknown northern source into southwestern Minnesota. These boulders remained on the landscape after the glaciers melted and are known as glacial erratics. Examples of glacial erratics include the Three Maidens, a group of boulders near the entrance to the monument. Glacial gouging produced features such as chatter marks, striations, and potholes in the Sioux Quartzite.
- Petroglyphs (prehistoric rock carvings). As many as 79 petroglyphs depicting various forms such as people, animals, and bird tracks were on 35 slabs of

rock surrounding the Three Maidens. When some of the petroglyphs were defaced in the late 19th century, they were removed from the monument. Seventeen of the original petroglyphs have been returned to the monument and are on display in the Visitor Center.

- Catlinite quarries. Quarrying catlinite has been a venerable tradition among American Indians for thousands of years, and it continues today in 56 intermittently active quarries in Pipestone National Monument.
- Sedimentary features in Sioux Quartzite. Fluvial features such as trough cross-bedding, ripple marks, and mudcracks in the Sioux Quartzite preserve a record of a river system that flowed through the area more than 1.6 billion years old.
- Reduction spots on Sioux Quartzite. White spots within pink or purple quartzite represent areas where iron and manganese were chemically reduced and removed by groundwater. This process may involve microbial growth and organic matter decay, evidence of a changing Earth atmosphere.
- Joints/Fractures. Near-vertical joints and fractures of an unknown origin occur in the Sioux Quartzite in sets that trend N20W and N45E.

The primary geologic resource management issues for the park include the following:

- Rockfall. Potential rockfall along the trails and in the quarries from fractured Sioux Quartzite is a safety issue. Rubble piles also pose a potential safety hazard for quarry workers.
- Flooding. Quarries often fill with water during spring flooding, which may also inundate roads, buildings, and other infrastructure. Bridges on Pipestone Creek impede flood waters, causing bridge railings to be destroyed. Water in the quarries may become contaminated, and when dry, contaminants in the dust may negatively impact quarry workers' health. The preferred alternative in the Final General Management Plan includes relocating the visitor center and residences out of the 100-year floodplain. Climate change models predict an increase in precipitation and temperature. Increased precipitation will exacerbate flooding issues.

The sedimentary features in the Sioux Quartzite capture a 1.7 billion–to–1.6 billion year old landscape, before the evolution of land plants and animals, consisting of braided streams dominated by sand and pebbles. Typical of braided stream environments, most of the finer-grained clay and silt particles were transported out of the system, so that the vertical accumulations of catlinite, with its unique composition, are rare. These mudstone deposits may have accumulated in abandoned channels or as a result of overbank flooding. When the quartz sand grains were buried and subjected to increasingly high pressures and temperatures, silica (quartz) cemented the sand grains into quartzite. The clay lithified into a fine-grained sedimentary rock known as argillite, which became known as catlinite, or pipestone.

From about 2.6 million to 11,000 years ago, continental glaciers flowed into Minnesota from the north, scouring the landscape and covering it with kilometer-thick (one kilometer is equivalent to 0.6 miles) sheets of ice. During the most recent glacial episode, the ice sheet split into two lobes, forming a highland known as the Coteau des Prairies in southwestern Minnesota. Located on the Coteau des Prairies, Pipestone National Monument supports a thin layer of till deposits that may be among the oldest in North America.

Products and Acknowledgments

The NPS Geologic Resources Division partners with the Colorado State University Department of Geosciences to produce GRI products. Geologists from the Minnesota Geological Survey reviewed GRI content.

GRI Products

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

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

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

Additional information regarding the GRI, including contact information, is available at http://go.nps.gov/gri. The current status and projected completion dates of products are available at http://go.nps.gov/gri_status.

Acknowledgments

Special thanks to: Josh Brinkman, Pipestone National Monument, for his overview of Pipestone National Monument and Mark Jirsa, Minnesota Geological Survey, for his geological overview of Pipestone National Monument during the scoping workshop. Seth Hendriks, Pipestone National Monument, and Mark Jirsa provided some of the photographs used in this report.

Review

Jason Kenworthy (NPS Geologic Resources Division)
Mark Jirsa (Minnesota Geological Survey)
Seth Hendriks (NPS Pipestone National Monument)

Editing

Michael Barthelmes (NPS Geologic Resources Division)

Report Formatting and Distribution

Michael Barthelmes (NPS Geologic Resources Division)
Jason Kenworthy (NPS Geologic Resources Division)

Source Maps

Morey (1983). National Park Service, Midwest Regional Office.
Hokanson et al. (1976). Soil Conservation Service.

GRI GIS Data Production

Dan Gilbert (Colorado State University)
Jim Chappell (Colorado State University)

GRI Map Poster Design

Kari Lanphier (Colorado State University)
Georgia Hybels (Colorado State University)

GRI Map Poster Review

Michael Barthelmes (NPS Geologic Resources Division)
Georgia Hybels (Colorado State University)
Rebecca Port (NPS Geologic Resources Division)
Jason Kenworthy (NPS Geologic Resources Division)

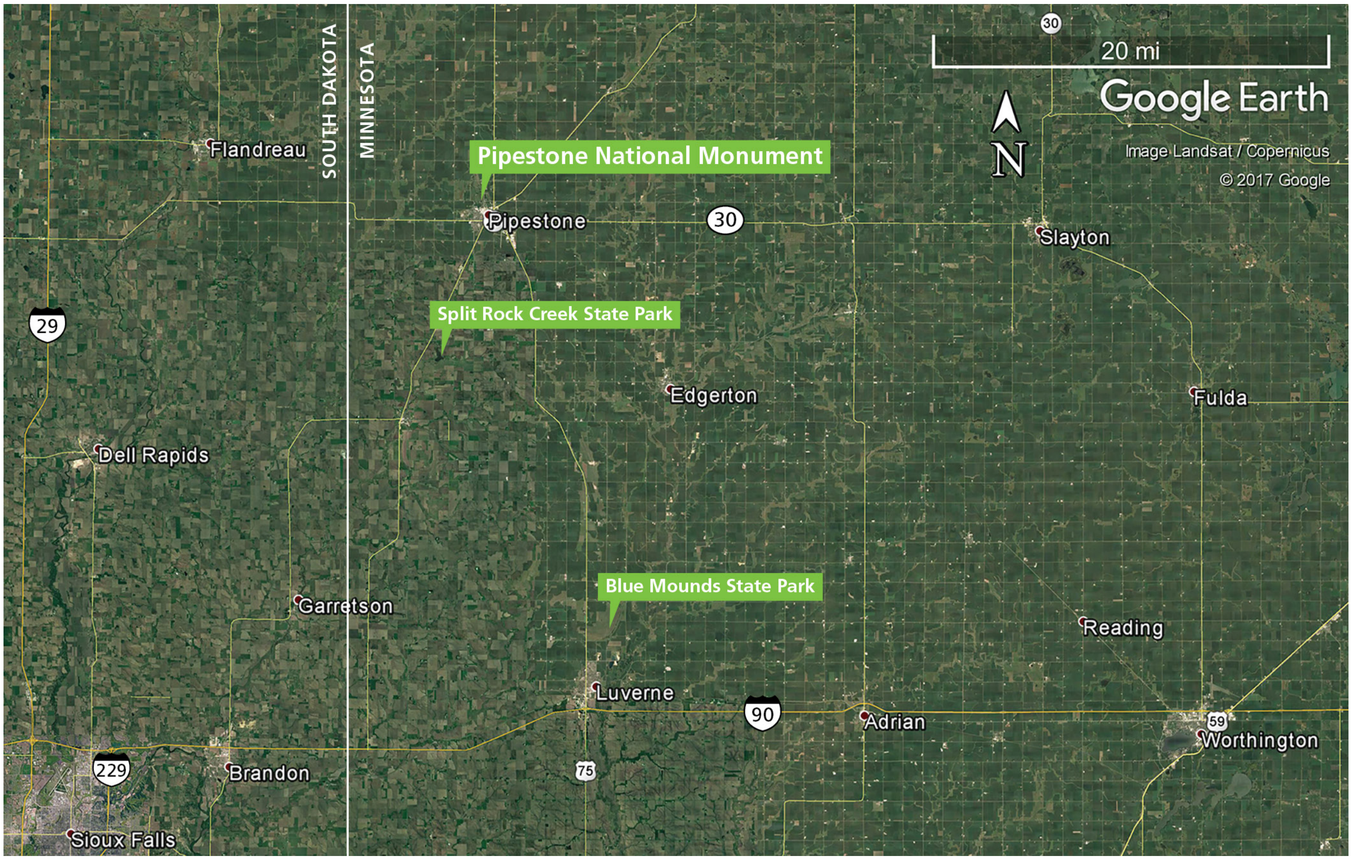


Figure 1. Location map of Pipestone National Monument in southwestern Minnesota. Imagery from Landsat/ Copernicus, © Google. Annotations by Jason Kenworthy (NPS Geologic Resources Division).

Geologic Setting and Significance

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

Geologic Setting

Located north of the city of Pipestone in southwestern Minnesota, the 122 ha (301 ac) of Pipestone National Monument protects the pipestone quarries that are sacred sites to American Indians (fig. 1). The monument's purpose is threefold: (1) administer and protect the quarries, reserving quarrying rights for American Indians of all tribes, (2) preserve, protect, and interpret cultural and natural resources associated with Pipestone National Monument, and (3) provide for enjoyment and benefit of all people (National Park Service 2008). The pipestone quarried by American Indians consists of the mineral catlinite, which is unique to Pipestone National Monument.

A north–south-trending ridge of Precambrian (fig. 2) Sioux Quartzite (geologic map unit **PCsq**) extends along the eastern edge of the monument, forming a 7.5–10 m (25–30 ft) high, west-facing escarpment (Morey 1981; Morey 1983; Morey and Setterholm 1987). The ridge extends for 5 km (3 mi) north of the monument and consists primarily of hard, vitreous, maroon to gray quartzite interbedded with thin layers of red catlinite, the altered clay that American Indians found easy to carve. The quartzite and catlinite beds dip (tilt) 3°–13° to the east. Well-developed joints also characterize Sioux Quartzite exposures. The joints trend northwest–southeast, east–west, and northeast–southwest (Morey 1983). The GRI GIS data include the locations from which geologic orientations, such as strike (compass direction) and dip of strata, were measured.

Any younger rock units that had overlain the Sioux Quartzite prior to approximately 2.6 million years ago were scraped off the landscape when continental glaciers flowed across Minnesota during the Pleistocene ice ages (Southwick 2002). During the ice ages, continental glaciers advanced several times into the region, depositing unconsolidated mixtures of clay, silt, sand, gravel, and boulders. These heterogeneous deposits are known as till (**Qgt**). In general, till in the monument is less than 3 m (10 ft) thick (Morey 1981). The glaciers also ground sediment into fine-grained, silt particles that were spread across the region by wind. Windblown silt is referred to as loess (**Ql**). Today, till and loess blanket most of the bedrock in the monument and provide the parent material for the soils supporting the restored tallgrass prairie (table 1).

During the most recent glacial episode, from about 75,000 to 10,000 years ago, an ice sheet estimated to be 1.6 km (1 mi) thick split into two lobes near the current northeastern border of South Dakota (Graham 2009). One lobe carved the present-day Minnesota River valley, and the other formed the James River valley. The non-glaciated land between the lobes, upon which Pipestone National Monument is located, formed a north-pointing triangular wedge approximately 320 km (200 mi) long and 160 km (100 mi) wide known as the Coteau des Prairies (French for 'highland of the prairies') (fig. 3). Because the Coteau des Prairies was not glaciated, the plateau contains tills from previous glaciations that are older than the glacial material deposited in the Minnesota River and James River valleys (Patterson 1995). Tills on the Coteau range between 800,000 and 500,000 years old, making them some of the oldest glacial deposits in North America (Jirsa et al. 2015; Bierman et al. 1999).

Elevations in the monument range from 300 m (980 ft) to 500 m (1,640 ft) above sea level. The relatively flat to rolling topography contains depressions and poorly drained soils. Pipestone Creek, Winnewissa Falls, and Lake Hiawatha represent the major hydrologic and fluvial geomorphic features in the monument (fig. 4; Jones et al. 2016). Entering the monument from the east, Pipestone Creek cascades over the Sioux Quartzite bluff, forming Winnewissa Falls. Winnewissa Falls is a feature known as a knickpoint, a part of a river or channel where there is a sharp change in channel slope, characteristic of all waterfalls. Knickpoints reflect different conditions and processes on the stream or river, and in Pipestone National Monument, Winnewissa Falls reflects the transition from erosion-resistant quartzite to relatively easily eroded unconsolidated alluvium and till.

From Winnewissa Falls, Pipestone Creek flows into Lake Hiawatha (fig. 4). In the spring of 1934, the Civilian Conservation Corps constructed a small dam

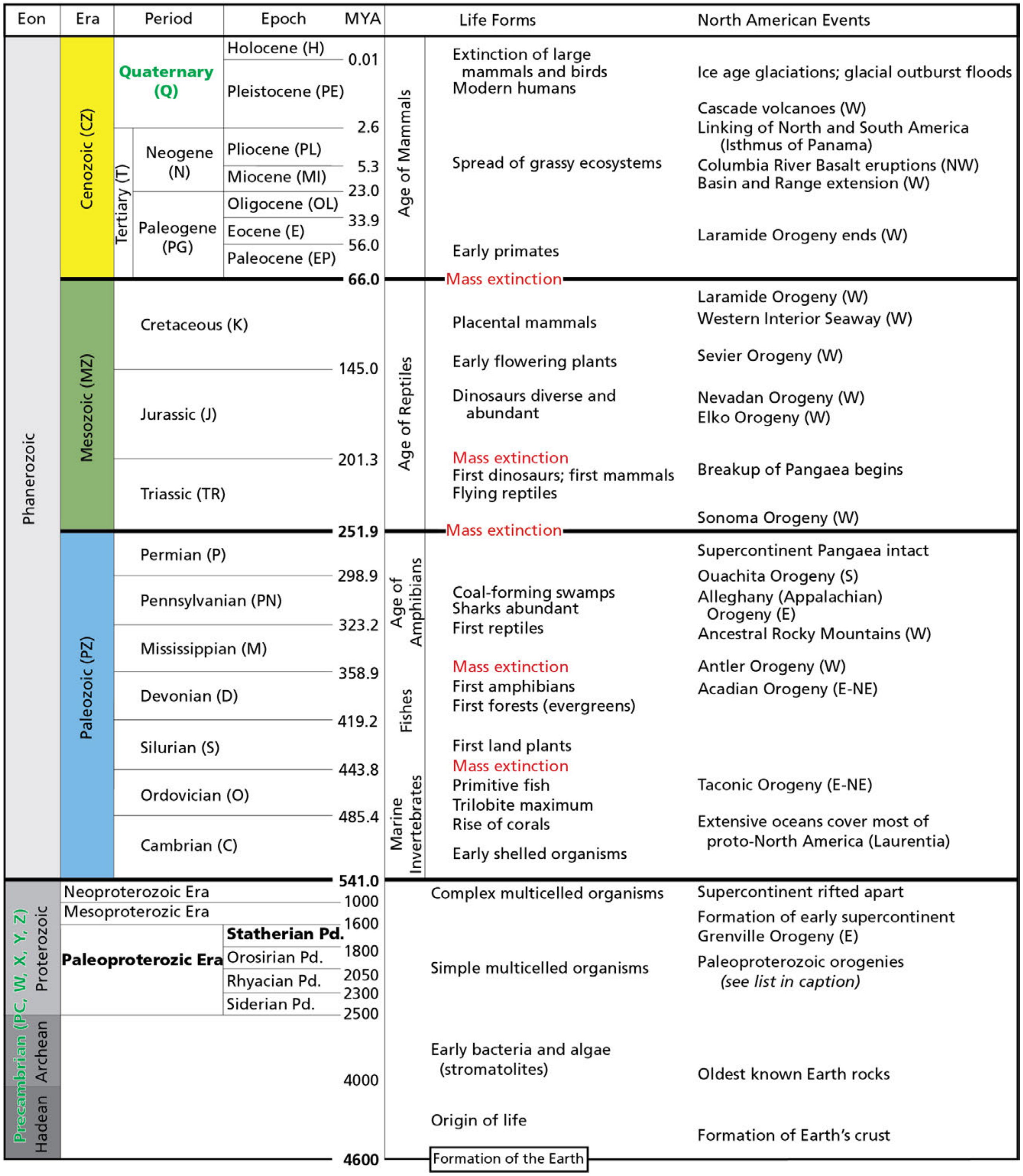


Figure 2. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. Time periods representing strata mapped in the Pipestone National Monument area are in green and at opposite ends of the time scale. GRI map abbreviations for each time division are in parentheses. Compass directions in parentheses indicate the regional locations of events. Boundary ages are millions of years ago (MYA). Pd. = "Period." Paleoproterozoic orogenies include Mazatzal (1,650 million–1,600 million years ago), Yavapai (1,710 million–1,680 million years ago), Trans-Hudson (2,000 million–1,800 million years ago), and Algoman (1,700 million–2,500 million years ago). 1,000 million years equals 1 billion years. National Park Service graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 7 May 2015).

Table 1. Description of geologic units mapped in Pipestone National Monument.

Period (Epoch) Age in MYA	Formation (map symbol)	Description
Cenozoic Era deposits (Ice age-present day)		
Quaternary (Holocene) 0.012-present	Alluvium (Qa)	Derived from Lamoure (silty clay loam) and La Prairie (loam) soils, which were deposited in the floodplain of Pipestone Creek. Covered by prairie vegetation.
Quaternary (Holocene) 0.012-present	Calcareous sand and gravel (Qcsg)	Derived from the silty clay loam and calcareous sand and gravel of Athelwold (At), Estelline (EsA) and Trosky (Ts) soils, which formed on the lower part of stream terraces and on glacial outwash plains (Hokanson et al. 1976). Mapped along the eastern border of the monument. Covered by prairie vegetation.
Quaternary (Pleistocene-Holocene) 2.6-0.01	Loess (Ql)	Derived from Ihlen Series silty clay loam soils found on 0–2% slopes (IhA) and 2–6% slopes (IhB) and silty clay loam Whitewood (Wh) soil formed on poorly drained 0–2% slopes. Mapped in the central portion of the monument. Covered by prairie vegetation. Loess is windblown silt and is common in areas that have been, or were close to, glaciated areas. Those areas were typically lacked substantial vegetation to hold silt in place.
Quaternary (Pleistocene) 2.6-0.12	Glacial Till (Qgt)	Derived from the silty clay loam of Brookings (BrA), Hidewood (Hd), Kranzburg (KrB), and Vienna (VbB2) soils that developed over calcareous till on side slopes of less than 3% adjacent to drainageways (BrA, Hd), on uplands (Hd, KrB), and on steeper slopes of 3–6% (VbB2). The till contains scattered pebbles and cobbles of basalt and quartzite. Glacial processes transported the basalt fragments into the area. The Sioux Quartzite provided the quartzite fragments. Generally less than 3 m (10 ft) thick. Mapped primarily along the western border of the monument. Covered by prairie vegetation.
Precambrian (Paleoproterozoic Era) bedrock		
Statherian 1,800-1,600	Sioux Quartzite (PCsq)	**Quartzite**. Hard, vitreous, red to pink, medium- to coarse-grained quartz sandstone. Sedimentary features characteristic of braided stream environments. Thin layers of well-indurated mudstone, siltstone, and fine-grained sandstone represent less than 5% of the formation. **Catlinite (Pipestone)**. Deep red mudstone consisting predominately of clay minerals pyrophyllite, muscovite, and diaspore. Contains little to no quartz and lesser amounts of hematite (red iron ore). Age: approximately 1,760–1,600 million years old.

Unconsolidated Pleistocene and Holocene units were mapped based on soils described in the Soil Survey of Pipestone County, Minnesota (Hokanson et al. 1976). Soil names, but not their descriptions, are mentioned in pipe_geology.pdf (in GRI GIS data); refer to Hokanson et al. (1976) for soils information. MYA: millions of years ago. Colors in "Period" column are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps. Colors in "Formation" column correspond to the GRI poster (in pocket).

(one of the park's historic structures) of Sioux Quartzite in order to increase the lake's size (Seth Hendriks, resource manager, Pipestone National Monument, written communication, 7 September 2016).

Pipestone Creek ultimately drains into the Lower Big Sioux River (Jones et al. 2016). The underlying Sioux Quartzite inhibits infiltration of rainfall and snowmelt and promotes surface flow during intense precipitation events. As a result, abundant rainfall or rapidly melting snowpack may cause flooding.

Sioux Quartzite

Deposited 1.76 billion–1.60 billion years ago (fig. 2), the Precambrian Sioux Quartzite (**PCsq**) forms the bedrock in the monument and surrounding region (table 1). The quartzite also represents part of a uniquely quartz-rich rock type exposed discontinuously across much of central North America from Newfoundland, southwestward to central Wisconsin, southern Minnesota, Colorado, New Mexico, Arizona, southern California, and adjacent parts of Mexico (Jones et

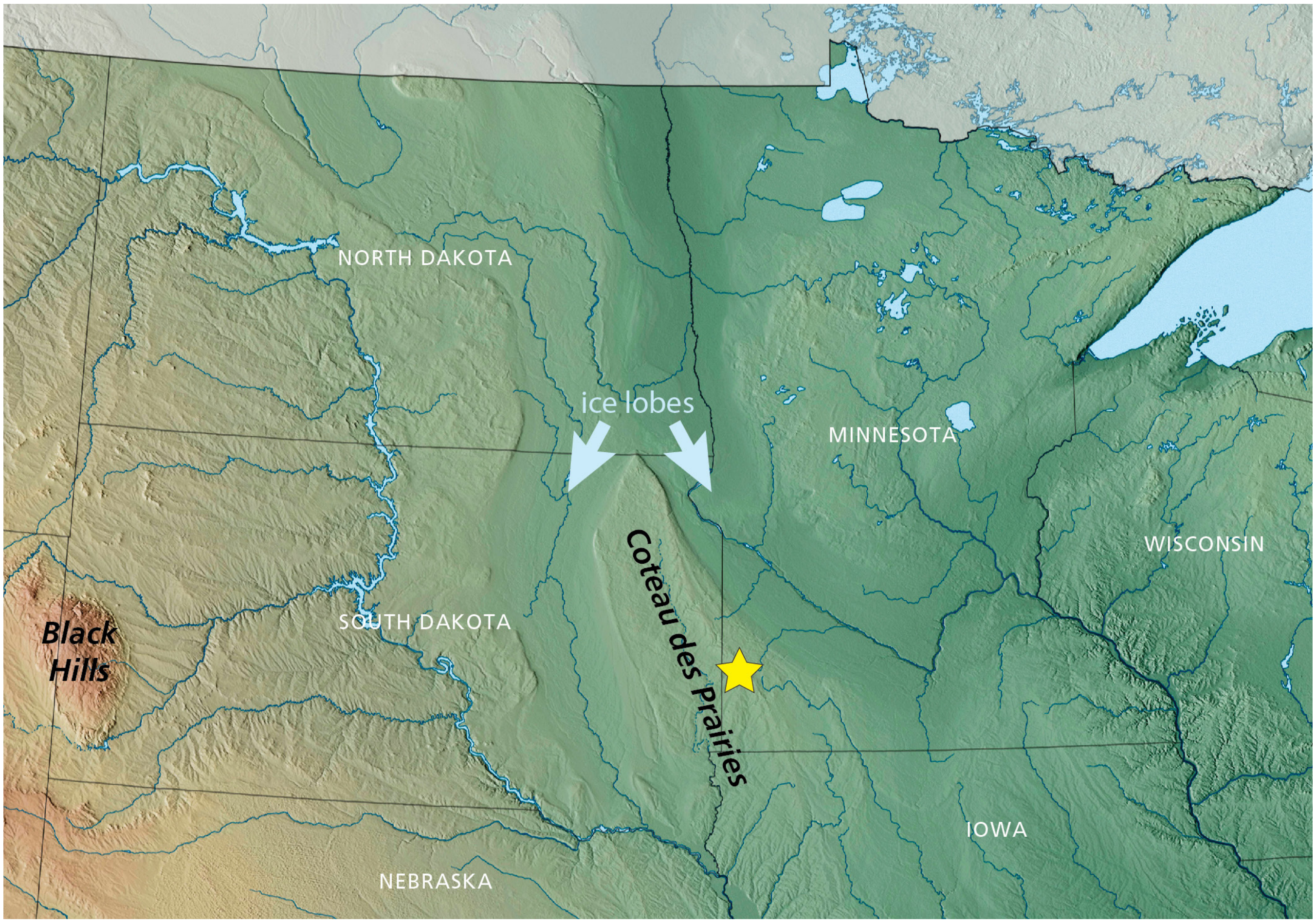


Figure 3. Relief map of a portion of the northern Great Plains showing the Coteau des Prairies, southwestern Minnesota. The most recent continental glacier split into two lobes and flowed around the borders of the Coteau des Prairies. The location of Pipestone National Monument is indicated with a yellow star. Relief map by Tom Patterson (National Park Service), available at http://www.shadedrelief.com/physical/index.html (accessed 1 June 2017).

al. 2009; Jirsa et al. 2015). Scattered exposures of the Sioux Quartzite portion of this extensive unit occur from New Ulm, Minnesota, to just west of Sioux Falls, South Dakota, and adjoining areas of Iowa and Nebraska. However, the Sioux Quartzite continues in the subsurface beneath younger strata as far west as the Black Hills (Jirsa et al. 2015). The quartz-rich unit is also thick. In southwestern Minnesota, the formation is estimated to be 1.3–1.7 km (4,300–5,600 ft) thick (Jirsa et al. 2015). According to Jirsa et al. (2015, p. 6), this exceptional unit is a "signature unit" that represents "a unique time period in the crustal, atmospheric, and biogenic evolution of our planet."

The Sioux Quartzite and similar formations represent a remarkable accumulation of quartz sand and the significant absence of any other mineral. Quartzites, in general, represent end products of erosion and weathering processes, which include chemical alteration and mechanical abrasion. Over millions of years, weathering processes and erosion of an ancient, largely granitic crust removed softer minerals, leaving behind highly durable quartz sand (Jirsa et al. 2015).

During the Paleoproterozoic (fig. 2), when rivers flowing across southwestern Minnesota deposited the sand that would become the Sioux Quartzite, Earth's atmosphere was transitioning from largely anoxic (containing little oxygen) to oxygenated. This transition may have been aided by the development of early photosynthetic organisms. At this time, the ancient crust, known as Laurentia, was located near the Tropics, and abundant rainfall, combined perhaps with early biogenic growth (microbial mats and crusts), altered non-quartz minerals to clay (Jirsa et al. 2015). Abundant quartz sand accumulated in the watersheds

Figure 4. Photographs of Winnewissa Falls and Lake Hiawatha, Pipestone National Monument. (top) Winnewissa Falls. Pipestone Creek flows over fractured Sioux Quartzite. National Park Service photograph by Jeff Rosenthal. (bottom) Lake Hiawatha. Water from the lake flows over a small dam composed of Sioux Quartzite that was constructed by the Civilian Conservation Corps in 1934. National Park Service photograph by Nathan King, available at https://www.nps.gov/media/photo/gallery.htm?id=FA92D98B-155D-4519-3E52BDFDA9CEDA12 (accessed 3 August 2016).

of streams, while clay and other fine-grained sediment washed away. Some of the clay, however, was deposited as thin layers of mud that eventually cemented to form pipestone (including catlinite). The lack of rooted vegetation in the Paleoproterozic contributed to high rates of run-off during storm events.

All continents formed by repeated collisions of Earth's crustal plates, and Laurentia was no exception. The Sioux Quartzite records a long period of relative crustal stability between two such collisional events known as the Yavapai (~1.7 billion–1.68 billion years ago) and the Mazatzal (~1.65 billion–1.60 billion years ago) Orogenies (mountain-building episodes). During quiescence between the two orogenies, the crust subsided and quartz sand was deposited, generating the extraordinary thickness of the Sioux Quartzite. Following deposition, deformation during the Mazatzal Orogeny folded the layers of sand or sandstone into broad basins. Hot groundwater produced by the deformation may have contributed to the transformation of the sandstone into quartzite (Jirsa et al. 2015).

Mineralogy

The formation consists of predominantly quartzite, but also includes minor amounts of quartz-rich siltstone, clayey siltstone, silty mudstone, and catlinite (Morey 1983). The finer grained rock units are easily eroded and rarely form outcrops. Quartzite, however, is highly resistant to weathering and erosion and crops out throughout the monument (fig. 5).

The mineral composition of the quartzite is relatively simple. In general, the quartzite consists of 90–95%

Figure 5. Photographs of Sioux Quartzite, Pipestone National Monument. (A). Steps carved into the Sioux Quartzite leading up to the top of the bluff on the Circle Trail. Photograph courtesy of Mark Jirsa (Minnesota Geological Survey). (B). Old Stone Face, Circle Trail, Pipestone National Monument. This cliff of Sioux Quartzite is known as "Old Stone Face," "Leaping Rock," and "The Oracle," depending on the visitor's perspective. NPS photograph by Seth Hendriks, Pipestone National Monument.).

quartz grains and 5–10% cement (Morey 1983). The grains are well-sorted, medium to fine sand-size, with edges rounded by quartz cement. Overgrowths of quartz cement are common in sedimentary rocks, and the abraded quartz overgrowths in the Sioux Quartzite indicate several cycles of deposition and erosion (Morey 1983). The quartzite also contains trace amounts of other minerals, such as magnetite, hematite, rutile, zircon, and tourmaline.

Quartzite is a dense, hard rock consisting primarily of quartz sand grains cemented together with silica (quartz). Quartzite differs from sandstone by breaking across the original sand grains, whereas sandstone typically breaks along the boundaries of the sand grains. Quartzite can be classified as either metamorphic or sedimentary (orthoquartzite), depending on the presence of metamorphic minerals. Proterozoic quartzites found in Wisconsin and elsewhere contain these minerals and are considered to be metamorphic rocks. The Sioux Quartzite in southwestern Minnesota contains minerals associated with burial (diagenetic minerals) and locally some minerals that may indicate low grade metamorphism, although these minerals are primarily found in South Dakota. Because metamorphic minerals have not been identified, the Sioux Quartzite in Pipestone National Monument is considered to be a sedimentary rock (Jirsa et al. 2015).

Temperature fluctuations in circulating groundwater may be responsible for the silica that cemented the sand grains together. Quartz dissolves in warm or hot water and precipitates out of solution when water cools. Burial and subsequent compaction of Sioux Quartzite sand would have produced heat, which would have dissolved the silica at the contact points between sand grains (a process known as pressure solution). Warm, silica-rich groundwater rising from more deeply buried layers would cement the cooler upper layers of sand. However, the source of a sufficient silica supply to cement such a large volume of sand remains to be found (Southwick et al. 1986; Jirsa et al. 2015). A thermal event related to the Mazatzal Orogeny may have driven warm, silica-rich groundwater through the sand, but this hypothesis also remains to be supported.

Examination of the framework quartz grains and their overgrowths indicates that the quartz cement formed early in the history of the Sioux Quartzite. Strain shadows and deformation lamellae that cross boundaries between quartz grains record a period of stress following cementation. A sericite-quartz-hematite matrix then replaced some of the strained quartz grains and overgrowth cement (Morey 1983).

The quartzite in the catlinite quarries in Pipestone National Monument is similar to this general description of the Sioux Quartzite, but some of the quartzite beds are finer grained, less well sorted, and contain as much as 39% matrix material (Morey 1983). Quartz overgrowth cement and evidence of subsequent stress is missing from some areas containing abundant matrix material, suggesting that the matrix material inhibited the development of quartz cement and acted as a lubricant taking up the strain when the rocks were stressed. The matrix material in the fine-grained quartzite, coupled with the lack of quartz cement and stress indicators, suggests that prior to any metamorphism, the matrix material was clay deposited contemporaneously with the quartz grains. Recrystallization of the original clay deposit occurred later in the history of the rock (Morey 1983).

Sedimentary Features in the Sioux Quartzite

The quartzite in the monument contains sedimentary features that represent a fluvial environment of deposition (Morey 1982; Jirsa et al. 2015). These features, summarized in the following section, include channels, cross-beds, ripple marks, and mud cracks (fig. 6). The most common features in the Sioux Quartzite of Pipestone National Monument and Blue Mounds State Park, approximately 35 km (22 mi) south of Pipestone National Monument, are channels containing festoon-like trough cross-bedding, swooping cross-beds that result from ripples cutting back and forth into each other (Morey 1983; Jirsa et al. 2015). The concave basal surface of the channels indicates that the channel scoured into the underlying strata. Relief on the channels ranges from several inches to several feet with widths of less than 0.3 m (1 ft) to more than 1.5 m (5 ft) (Morey 1983). Some channels, however, are as much as 1.5 (5 ft) deep and 9 m (30 ft) wide.

In general, each channel begins with structureless beds characterized by granule-size quartz grains or mud chips dispersed in a finer grained ground mass. Strata overlying the structureless beds contain trough cross-bedding ranging from 5 cm (2 in) to 15 cm (6 in) thick, although some cross-beds are as much as 1.5 m (5 ft) thick (Morey 1983). The grain size in each group of

Figure 6. Photographs of ancient sedimentary features found in the Sioux Quartzite. (A) Ripple marks (quarter for scale). The asymmetry of the ripples, with each crest separating a gradual slope and steeper limb, suggests that they were formed by a river current flowing from right to left in the photo, as steeper limbs form downstream. (B) Trough-shaped cross-beds (see fig. 7) also suggest deposition in a laterally migrating channel. Photographs courtesy of Mark Jirsa (Minnesota Geological Survey).

cross-beds within any given channel decreases upward and laterally, forming a broadly fining-upward sequence of strata.

The channels generally occur in sets where younger channels overstep and truncate older channels. As a result, individual beds and groups of bed form a broadly lenticular geometry.

Within individual channel deposits, fine-grained beds of mudstone, including some catlinite, occur as thin, nearly planar beds or laminae of limited lateral extend. Distribution of the fine-grained beds records the final infilling of a channel or deposition resulting from overbank flooding.

The major catlinite beds occur as discontinuous layers between much larger quartzitic lenses and form discrete layers as much as 1 m (3 ft) thick. The beds may be traced for fairly long distances or they may appear as lenses only several tens of feet long (Morey 1983). Many of the catlinite beds grade laterally from claystone to silty claystone to clayey siltstone and ultimately to argillaceous quartzite (quartzite containing clay). Upper surfaces of the catlinite beds are characterized by sets of planar cross-beds, asymmetrical and symmetrical ripple marks, and mud cracks (fig. 6) (Morey 1983).

Paleocurrent directions measured from the axial plane of festoon cross-bedding, which parallels the paleocurrent flow, indicate a predominant southward to south-southeastward paleocurrent direction (Morey 1983). Other current direction indicators, such as planar cross-beds and asymmetrical ripple marks, have diverse orientations.

No Proterozoic fossils have been discovered in the Sioux Quartzite at Pipestone National Monument (Hunt et al. 2008). However, according to Jirsa et al. (2015), there may be indirect evidence of life in the quartzites. Irregular round white areas visible in outcrops may result from reduction and dissolution of iron from the sand (probably before it was cemented into quartzite) by the presence of bacterial fragments (Hofmann 1991; cited by Jirsa et al. 2015). Organic debris, such as microbial crusts or mats, could have been eroded and incorporated into the sediment of the river system. Alternatively, microbial colonies may have developed within the sandy stream system during suitable environment conditions. Thus, although there appear to be no fossils in the Sioux Quartzite, the white spots are similarly indicative of early life forms (Jirsa et al. 2015).

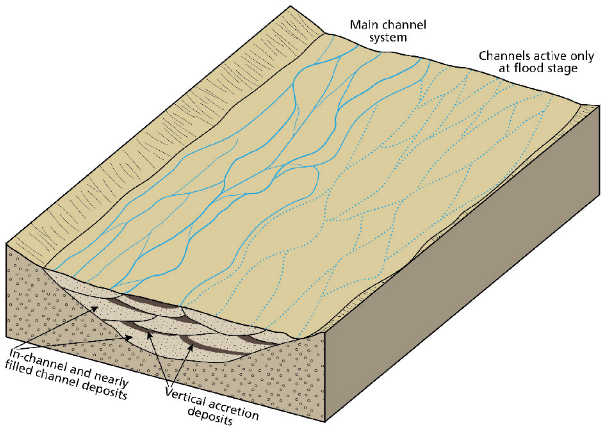
Paleoenvironmental Implications

The extensive trough cross-bedding, the lenticular nature of the strata, and the general lack of silt- and clay-size material record deposition by fluvial processes associated with a braided-stream system (fig. 7). As the name implies, braided-stream systems consist of branching and coalescing channels filled with sand and silt during high stream flow and fewer interlacing channels during low flow.

The Sioux Quartzite in Pipestone National Monument includes four major types of deposits found in modern braided-stream systems: channel-floor lag deposits, in-channel deposits, nearly filled channel deposits, and vertical accretion deposits (Allen 1965; Morey 1983; Mial 1992). Channel-floor lag deposits are found in the lower parts of many channels. Sand-size detritus that flowed through the system as bed-load material fills most channels and is responsible for the trough cross-bedding. Finer grained sediment was deposited in shallow water at the edges of channels, in channels nearly filled with sediments, or in interchannel areas that received deposits during floods.

Catlinite beds in the Sioux Quartzite reflect vertical accretion deposits. Vertical accretion deposits are not common in braided stream environments for several reasons (Morey 1983; Morey and Setterholm 1987; Scott et al. 2006; Jirsa et al. 2015). First, finer grained material such as silt and clay typically gets transported through the system without significant accumulation. Secondly, vertical accretion deposits form only during major floods when the river spills from its channel. Lastly, fine-grained vertical accretion deposits tend to be easily eroded by the relatively rapidly migrating channels in a braided stream system.

Catlinite in Pipestone National Monument, therefore, reflects the uncommon accumulation of fine grained material in a braided river system dominated by coarse grained detritus and fast-flowing currents. For example, catlinite is not present in the Sioux Quartzite in Blue Mounds State Park, although both areas represent similar braided stream environments (Jirsa et al. 2015).



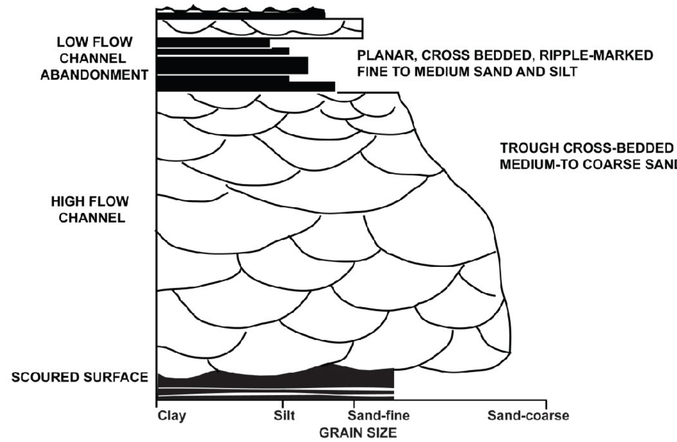


Figure 7. Braided stream system and schematic vertical section of the Sioux Quartzite of southwestern Minnesota. Features in a typical vertical, braided stream sequence consist of trough cross-bedded sandstone deposited in active channels, ripple-marked sandstone as current decreases, and claystone deposited when channels are abandoned and fine particles settle out of the ponds and overbank puddles. In the Sioux Quartzite, trough cross-bedded units are typically pale colors of purple and pink. Less abundant and generally thinner planar cross-bedded units tend to be much darker colored red and purple. Modified from Jirsa et al. (2015, figures 3 and 4). Photograph of modern braided stream system available online from Alaska ShoreZone imagery: https://toolkit.climate.gov/case-studies/shorezone-tool-coastal-resilience.

Post-Depositional Weathering and Alteration

The Sioux Quartzite also offers a remarkable glimpse into the interaction between groundwater flow and sediment deposition during the Proterozoic of southwestern Minnesota. The consistent color pattern in the Sioux Quartzite (fig. 6) may reflect groundwater flow rates that were influenced by deposition within the braided stream system (Jirsa et al. 2015). Thin coatings of hematite (red iron mineral) and perhaps manganese (purplish element) have been found on individual sand grains, suggesting that the grains were colored during and just after deposition of the sand and prior to silica cementation. The presence of hematite, an iron oxide, also suggests that the coloration was associated with the oxygenation of Earth's atmosphere.

Lighter colors and thinner coatings are associated with sand grains, while thicker coatings and darker colors

Figure 8. Photograph of calumet pipes on display in the Pipestone National Monument visitor center. Photograph courtesy of Mark Jirsa (Minnesota Geological Survey).

characterize clay layers. According to Jirsa et al. (2015), the color variation may involve the contrast between aquifers, groundwater reservoirs, and aquitards, units that retard groundwater flow. The coarse-grained, trough cross-bedded channel sands would have been more permeable than the finer-grained clay layers, allowing groundwater to circulate through the sediment, depositing thinner coatings. On the other hand, finer-grained clay layers would have prevented rapid groundwater flow, resulting in more residence time and consequently, thicker layers and more coloration. In addition, if the clay layers were exposed at the surface, desiccation may have occurred during dry periods, leading to oxidation of iron and manganese and a darker coloration (Jirsa et al. 2015).

The Sioux Quartzite in Pipestone National Monument has also been altered by near-surface weathering processes, especially by circulating groundwater. Circulating groundwater selectively dissolved hematite along near-vertical joint faces, resulting in light-colored zones that contrast with the typically pink or red quartzite. These zones are generally less than 5 cm (2 in) wide, but some are as much as 46 cm (18 in) wide (Morey 1983).

Circulating groundwater may also be responsible for the yellowish-gray to white weathered zone that occurs within 0.6–0.9 m (2–3 ft) of the contact between the bedrock and overlying till (Morey 1983). This zone lacks hematite, contains less sericite and quartz than does fresh bedrock, and may have a larger grain size and be better sorted than the adjacent unweathered bedrock, implying that circulating groundwater dissolved hematite, matrix material, and smaller detrital framework grains.

Poorly cemented to almost friable zones of quartzose sandstone that occur parallel to bedding in the subsurface reflect similar characteristics as the bleached rock associated with joint faces and the till-bedrock contact (Morey 1983). Typically, an outer rim of bleached rock similar to the light-colored quartzite found along joint faces transitions into a weathered zone similar to the till-bedrock interface. This weathered zone passes abruptly into a zone where all of the original mineral constituents, other than large framework grains, have been removed. These weathered zones indicate groundwater activity at the bedrock surface and within open fractures, such as joint sets and bedding planes. However, the timing of the groundwater activity is not known. According to Morey (1983, table 2), weathering and dissolution could have occurred at any time before the onset of Pleistocene glaciation, approximately 2 million years ago.

Catlinite

Layers of catlinite in Pipestone National Monument contrast markedly with the quartzite. The deep red to pale orange claystone beds lack appreciable quantities of quartz and appear massive except for a few shaly parting planes parallel to the bedding (Morey 1983). In 1981, G. B. Morey of the Minnesota Geological Survey noted that catlinite was commonly called “pipestone” because it was used by American Indians to make their ceremonial pipes (Morey 1981). The terms “catlinite” and “pipestone” became interchangeable. However, pioneering research by Gundersen (1982, 1984, 1987, 1988, 1991, and 1993) documented that red pipestones from different areas, although appearing similar, were mineralogically distinct.

Mineralogical studies of pipestones throughout North America have determined that true catlinite comes from one source: the quarries at Pipestone National Monument. Definitive mineralogical data support Pipestone National Monument as the type locality of catlinite, which means that pipestone from any other location is compared to catlinite found at the monument to determine if it is true catlinite (Scott et al. 2006; Boszhardt and Gundersen 2014; Wisseman et al. 2011, 2012). The monument’s quarries preserve at least five, north–south-trending exposures of catlinite layers that extend for approximately 1.2 km (0.75 mi) (see GRI poster in pocket).

Catlinite consists predominantly of very fine grained sericite (a mica similar to muscovite), kaolinite, diaspore, and lesser amounts of pyrite and hematite, the iron-rich mineral that provides catlinite’s red color (Berg 1938; Gundersen 1982; Morey 1983). Catlinite contains little to no quartz (Morey 1981; Boszhardt and Gundersen 2014; Wisseman et al. 2011, 2012; National Park Service 2015a). Pyrophyllite, which can be etched with a fingernail, occurs locally as small white specks or as lenses as much as 10 cm (4 in) long and 5 cm (2 in) thick (Morey 1983). The lack of quartz and occurrence of soft clay minerals makes catlinite ideal for carving into pipes and figures using simple hand tools.

Catlinite clay minerals provide significant information about post-depositional alteration. The original composition of the clay is not known, but the ubiquitous presence of sericite implies recrystallization of a potassium-rich clay (Morey 1983). Sericite is a common alteration mineral of potassium feldspar, especially in areas subjected to hydrothermal alteration.

Kaolinite, diaspore, and pyrophyllite also offer evidence of post-depositional recrystallization. Kaolinite and diaspore in deeply buried parts of the Sioux Quartzite terrain document diagenetic processes involving potassium feldspar dissolution prior to recrystallization (Morey 1983). Pyrophyllite may form by a metamorphic reaction involving sericite, quartz, and water, with concurrent release of some potassium, or it may form by a metamorphic reaction involving kaolinite and/or diaspore, without the release or consumption of potassium. In either case, the presence of pyrophyllite implies that the rocks that are now exposed in Pipestone National Monument were once deeply buried (Berg 1938; Morey 1983).

Rapid burial helped preserve the Midcontinent pipestone deposits, including the catlinite in the monument. After deposition, hydrothermal fluids ranging from ~50°–120° C (122°–248° F) and increased burial produced low-to-medium temperature metamorphic conditions, which altered the pipestone (Wisseman et al. 2012). The fluids, which likely originated from a mountain building event in either the late Precambrian or during the Paleozoic Era, contained potassium (K^+), magnesium (Mg^+), and metals such as lead (Pb) and zinc (Zn). These minerals reacted with the fine-grained deposits to form common minerals such as potassium feldspar, illite, mixed-layered illite/smectite, and muscovite (Wisseman et al. 2012). Morey (1983) noted that recrystallization of the original clay could have occurred at any time prior to Pleistocene glaciation. Wisseman et al. (2012) suggested an orogeny "such as" the Alleghany Orogeny (mountain-building episode about 300 million years ago) to the east could be responsible. The mountain building event that altered the Sioux Quartzite is the much older (~1.6 billion years ago) Mazatzal Orogeny. Alteration minerals in the Sioux and similar quartzites in the midcontinent yield ages suggesting hydrothermal alteration 1.4 billion years ago during a continent-scale igneous event (Medaris et al. 2003; M. Jirsa, geologist, Minnesota Geological Survey, written communication, 17 March 2017). In addition, the distinctive catlinite mineral assemblage indicates that Pipestone National Monument deposits were exposed to a higher-temperature alteration than pipestone found in Ohio, Wisconsin, Illinois, or Missouri (Wisseman et al. 2012).

Catlinite and Culture

Prior to detailed analysis of pipestone mineralogy, most archeological specimens were identified as catlinite (Emerson and Hughes 2001). However, documenting the unique mineralogy of catlinite has revised archeologists' understanding of aboriginal use of catlinite and long-distance trading routes. For example, mineralogical studies of Adena/Hopewell pipes in the Great Lakes and Upper Midwest region determined that the pipes were carved from catlinite rather than Ohio pipestone, implying that southwestern Minnesota catlinite was traded as early as 500 BCE (Boszhardt and Gundersen 2014).

Historical and archeological evidence also suggests that the catlinite quarries of southwestern Minnesota were not continuously used. Quarrying occurred during the Middle Woodland period (200 BCE–500 CE), was abandoned during the Mississippian culture (800–1600 CE), and then revitalized after about 1,300 CE (Emerson and Hughes 2001; Wisseman et al. 2011). In addition, Hopewell period (ca. 1–400 CE) catlinite pipes found in Ohio's Tremper Mound and in Wisconsin, but not Illinois, reveal a direct west-to-east route from the southwestern Minnesota quarries in Pipestone National Monument through Wisconsin to Ohio from about 50 BCE to 79 CE (Emerson et al. 2005).

Quarrying increased in the 1600s and the Yankton Sioux eventually took control of the quarries. Painter George Catlin visited the region in 1836. In addition to his paintings, Catlin collected samples of the claystone and gave them to mineralogist C. J. Jackson to analyze. Jackson determined that the claystone had a unique composition, and believing it only occurred where Catlin found it, Jackson named the claystone "catlinite" in Catlin's honor (Morey and Setterholm 1987). More than 100 years later, Jackson's premise was supported by laboratory analysis. For more information about Catlin and his artwork, visit http://americanart.si.edu/collections/search/artist/?id=782 (accessed 20 April 2016).

Henry Wadsworth Longfellow mentioned the "great Red Pipe-stone Quarry" in his Song of Hiawatha, and, in 1838, explorers Nicollett and Fremont carved their names in a quartzite layer above Winnewissa Falls (M, Jirsa, geologist, Minnesota Geological Survey, written communication, 15 March 2017). Their initials are still visible today.

American Indians carved catlinite into calumet pipes, the elbow-shaped and disk-shaped types of pipe commonly used in ceremonies and rituals (fig. 8). Calumets became known as peace pipes because they were used in treaty ceremonies.

Between 1840 and 1858, commercial interests began to move into the area and conflicts arose between these interests and the Yankton Sioux, who were being pressured to move to a reservation in south-central South Dakota. In 1889, a bill was passed that gave the Yankton authority to retain 260 ha (650 ac) at Pipestone. The federal government took control of the quarry in 1928, and in 1937, President Roosevelt established Pipestone National Monument (Josh Brinkman, Pipestone National Monument, biological technician, personal communication, 19 August 2008). As an indication of the cultural significance of pipestone to the identity of Minnesota, a slab of pipestone inscribed with "MINNESOTA" was donated to the Washington Monument to represent the state (Jacob 2005). The stone is installed on the 220-foot level and is one of 193 commemorative stones installed in the monument (Jacob 2005).

American Indians continue the three-thousand-year-old tradition of quarrying and carving pipestone. Currently, the monument has 56 intermittently active quarries. Throughout the summer, local American Indians carve pipestone in the Upper Midwest Indian Cultural Center, located inside the visitor center.

Proposed Development at Pipestone National Monument

The preferred alternative in the *Final General Management Plan* for Pipestone National Monument emphasizes the setting, site history, and spiritual significance of the national monument (National Park Service 2008). The preferred alternative supports the following changes to the monument:

- Removing the existing visitor center and parking lot from among the quarries,
- Removing the entry road and restoring the natural contours of the land,
- Removing 0.8 ha (2 ac) of buildings and impermeable surfaces from the floodplain.

These changes will allow visitors to observe the site as it appeared in prehistoric times and to sense the site's significance to American Indians.

The alterations to the landscape will also improve water flow through the monument and reduce the damage from flooding on park infrastructure. Currently, the visitor center and residences are in the 100-year floodplain. Bridges on Pipestone Creek impede floodwaters, destroying bridge railings (NPS 2016a). Snow melt, rain, and an elevated groundwater level result in frequent flooding of the quarries in the spring. Groundwater is pumped from the quarries, but the water may be contaminated and when the quarries dry, contaminants in the dust may sicken quarry workers. Climate change models predict an increase in precipitation, which will exacerbate flooding issues.

Further information addressing the management history, cultural resources, and external threats to the monument is available from *Managing the Sacred and the Secular: an Administrative History of Pipestone National Monument* by Hal Rothman and Daniel Holder (1992) (https://www.nps.gov/parkhistory/online_books/pipe/adhi.htm, accessed 26 July 2016).

Geology and Ecosystem Development

Pipestone National Monument landscape illustrates the notable connection between geology and ecosystem development. The monument's distinct geologic and hydrologic features combine to provide an unusual array of habitats supporting a diverse assortment of over 500 prairie plant species, 26 fish species, 45 macroinvertebrate species, 9 reptiles and amphibians, 25 mammal species, 56 families of insects, and about 100 bird species (NPS 2016b).

The north–south trending Sioux Quartzite outcrop that bisects the monument features a narrow Bur Oak (*Quercus macrocarpa*) Woodland community and the Northern Tallgrass Quartzite Outcrop community. The Bur Oak Woodland community covers 1.9% of the monument and occupies the rocky and moist soils on the downslope side of the bluff. The Northern Tallgrass Quartzite Outcrop vegetation grows on the rocky slope above the Bur Oak Woodland community and includes 5.4% of the monument (Diamond et al. 2014).

Areas of unbroken sod support the Sioux Quartzite prairie, consisting of rare habitats, federally listed threatened and endangered species, and globally rare remnant plant communities. Ten vegetation types, dominated by tallgrass prairie communities, have been mapped in the monument (Diamond et al. 2014). Central Mesic Tallgrass Prairie cover 57.3% and Restored Tallgrass Prairies grow on 24.4% of the landscape. A small floodplain forest and riparian shrubland habitats occur adjacent to Pipestone Creek (Diamond et al. 2014).

The extensive plant community at Pipestone National Monument has been described as "quite unique and species-rich" (Diamond et al. 2014, p. 46), and the Nature Conservancy has declared the 8 ha (20 ac) of Sioux Quartzite prairie type as "endangered throughout its range" (NPS 2016b).

Geologic Features, Processes, and Resource Management Issues

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

During the 2008 scoping meeting (see Graham 2009) and 2016 conference call, participants (see Appendix A) identified the following features, processes, and resource management issues. Each is discussed in tables 2 and 3 in the context of relevant geologic map units.

Features and Processes (table 2)

- Fluvial features
- Eolian features
- Glacial features
- Petroglyphs
- Catlinite
- Pipestone quarries
- Ancient sedimentary features
- Joints and fractures
- Quartzite with reduction spots

Resource Management Issues (table 3)

- Flooding
- Rockfall and quarry use

Geologic Resource Management

The Geologic Resources Division provides technical and policy support for geologic resource management issues surrounding geologic heritage, active processes and hazards, and energy and minerals management. Contact the division (http://go.nps.gov/geology) for assistance with resource inventories, assessments and monitoring; impact mitigation, restoration, and adaptation; hazards risk management; law, policy, and guidance; resource management planning; data and information management; and outreach and youth programs (Geoscientists-in-the-Parks and Mosaics in Science).

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

Resource Management Guidance for Geologic Features and Processes

In general, the southwestern Minnesota landscape captures a distinctive Precambrian braided stream system, a topography sculpted by Pleistocene glaciers, and a Holocene drainage system that developed during the Quaternary Period. Additional information regarding the processes associated with the geologic features in Pipestone National Monument may be found in the following references.

Eolian Resources

Eolian processes refer to wind-blown erosion, transportation, and deposition of sediments (Lancaster 2009). Features created by eolian processes include depositional landforms and deposits such as dunes, loess, sand sheets, as well as erosional forms such as desert pavement, yardangs, and ventifacts. In the Pipestone National Monument area, loess is the primary feature associated with eolian processes. The NPS Geologic Resources Division Aeolian Resource Monitoring website, http://go.nps.gov/monitor_aeolian (accessed 24 April 2017), provides additional information.

Fluvial Geomorphology

In the Geological Monitoring chapter about fluvial geomorphology, Lord et al. (2009) described methods for inventorying and monitoring geomorphology-related vital signs, including: (1) watershed landscape (vegetation, land use, surficial geology, slopes, and hydrology), (2) hydrology (frequency, magnitude, and duration of stream flow rates), (3) sediment transport (rates, modes, sources, and types of sediment), (4) channel cross section, (5) channel planform, and (6) channel longitudinal profile. These methods may be utilized on any size of river or stream, from large rivers such as the Mississippi to creeks as small as Pipestone Creek.

Table 2. Summary of features and processes associated with the geologic map units.

Map Unit (symbol)	Features and Processes
Alluvium (Qa)	**Fluvial Features** The sediment in Pipestone Creek continues to be transported and temporarily deposited in the channel, while seasonal flooding deposits finer grained silt and clay in the floodplain (Site 2). Streams constantly adjust their gradient by eroding upstream and this headward erosion has resulted in Winnewissa Falls, a fluvial geomorphic feature known as a knickpoint (fig. 4).
Calcareous sand and gravel (Qcsg)	**Soil Features** Silty clay loam underlain by calcareous sand and gravel (Athelwold, Estelline, and Trosky soil series). Deposited over water-laid or wind-blown material. Refer to Pipestone County Soil Survey (Hokanson et al. 1976) for additional information regarding properties of the soils from which this unit was derived (see table 1).
Loess (Ql)	**Eolian Features** Windblown silt derived from glacial erosion of sediment and bedrock.
Till (Qgt)	**Glacial Features** Till: Deposits of heterogeneous, unsorted clay, silt, sand, and gravel. May be among the oldest till in North America.Glacial erratics: Granite boulders, such as the Three Maidens, from an unknown northern origin that were left on the surface when the glaciers melted (fig. 9; Site 4). **Petroglyphs** Prehistoric rock carvings depict various images such as people, animals, and bird tracks. In 1888 or 1889, 79 petroglyphs on 35 slabs of rock around the Three Maidens were removed in order to preserve them from further vandalism. Some have been returned to the monument, and 17 are now on display in the Visitor Center (National Park Service 2015b).
Sioux Quartzite (PCsq)	**Catlinite** Pipestone National Monument preserves the only recognized location of catlinite (fig. 8). **Glacial Features** As glaciers receded, the rock exposures were sculpted by dusty winds that are common along glacial margins and pronounced at this time of no vegetation cover. The wind polished, pitted, and faceted the rock surfaces (fig. 10; Site 8; M. Jirsa, geologist, Minnesota Geological Survey, written communication, 16 March 2017) **Pipestone Quarries** Source of catlinite for pipestone carvings (fig. 11). See also https://www.nps.gov/pipe/learn/historyculture/quarrying.htm. **Ancient Sedimentary Features** Horizontal bedding layers (Site 6). Trough cross-bedding formed when new layers of sand were deposited on older, lithified layers (fig. 6; Sites1, 2, 11, 13). Ripple marks formed from current flow (fig. 6; Site 7). Trough cross-bedding and ripple marks suggest that these 1.7 billion year old streams flowed, in general, from west to east/southeast. Mudcracks formed when standing water evaporated and the mud dried (desiccation) (fig. 6; Sites 9, 10). **Reduction Spots** White spots appear as circular and irregularly shaped patches within pink or purple quartzite. The spots typically cross-cut lines of bedding or layering and are inferred to be areas where iron and manganese were chemically reduced and removed by groundwater. This process may involve organic matter, which, upon decay, uses oxygen from the iron minerals, producing free iron that is more easily removed by groundwater. Microbial growth blossomed during this time period, supporting this organic decay scenario and providing evidence for a changing Earth atmosphere (Jirsa et al. 2015). **Joints/Fractures** Near-vertical joints occur in sets that trend N20W and N45E (fig. 12). Near-horizontal joints are present in cliff faces and quarries. The joints control the orientation of the quarries as it is easier to remove rock along pre-existing joints than break solid rock. The joints and fractures cannot be tied to specific crustal events. They may be associated with compression caused by the Mazatzal Orogeny, or they may represent more recent uplift and erosion of overlying crustal material that allowed the Sioux Quartzite to expand and crack. Some joints may represent uplift of the bedrock surface following the melting of thick glacial ice. Or, the fractures may be a product of all three crustal events. Locally, the joints serve as conduits for groundwater. Local surface drainage patterns may be influenced by fractured rock because fractured rock is more easily eroded than rocks that are not fractured.

Site numbers are from the Geology Trail brochure available in the Pipestone National Monument visitor center. The brochure provides a self-guided tour to geological features along Circle Trail. Colors correspond to the poster (in pocket)

Table 3. Summary of geologic resource management issues associated with the geologic map units.

Map Unit (symbol)	Potential Geologic Issues
Alluvium (Qa)	**Flooding** Flash flooding often occurs following abundant rainfall, quick snowmelt on frozen ground, or a combination of rainfall on already saturated ground (fig. 13). The indurated Sioux Quartzite inhibits infiltration of precipitation, so sheets of water drain across the monument from east-to-west, often filling quarries (fig. 14). Flood water may overtop the escarpment south of Winnewissa Falls, causing damage to trails and the bridge at Winnewissa Falls (NPS 2008). Flooding has filled Lake Hiawatha with sediment so that less than 0.6 m (2 ft) of water storage is left in the lake. Flooding dislodges aquatic macroinvertebrates (periphyton), reducing stream productivity. Chemical pollutants from upstream threatens the health of floodplain biota, and flood debris detracts from the monument's aesthetics.
Loess (Ql)	These units occupy relatively flat topography, with slopes generally less than 2%, and they are covered by prairie grass. Slope movement occurs on even these gentle slopes, but movement occurs over a scale of thousands of years. Thus, erosion and slope movements are not severe
Sioux Quartzite (PCsq)	**Rockfall and Quarry** UseRockfall along the trails and in the quarries from fractured Sioux Quartzite pose a potential resource management issue. Moisture enters the thinner layers in the quartzite, and physical and chemical weathering erodes these layers faster than the thick, overlying strata (Site 14). Frost-heave along vertical and shallowly-dipping (bedding parallel) joints may dislodge blocks. Undercut cliffs may collapse. Rubble piles also pose a potential safety hazard for quarry workers (fig. 11). All quarrying activity requires a permit as outlined: https://www.nps.gov/pipe/learn/management/quarry-permits.htm.

Site numbers are from the Geology Trail brochure available in the Pipestone National Monument visitor center. The brochure provides a self-guided tour to geological features along Circle Trail. Colors correspond to the poster (in pocket)

Figure 9. Photograph of the Three Maidens at sunset, Pipestone National Monument. Composed of granite rather than quartzite, the boulders are glacial erratics left on the landscape when the Pleistocene glaciers melted. The individual "maidens" may have originally been part of one large boulder. National Park Service courtesy of Seth Hendriks.

Glacial Deposits and Erosional Features

The massive continental ice sheets that flowed from the Arctic into Minnesota during the Pleistocene Epoch (2 million to approximately 20,000 years ago) scoured and reshaped the landscape. In general, glacial deposits and features include those created or carved by glaciers, those deposited by rivers flowing beneath or out of glaciers ("glaciofluvial"), or deposited in lakes near glaciers ("glaciolacustrine"). In Pipestone National Monument, glacial deposits of till and glacial erratics, such as the Three Maidens, form the primary record of glacial advances into the area.

Slope Movements

Slope movements are the downslope transfer of soil, regolith, and/or rock under the influence of gravity. In Pipestone National Monument, slope movements are concentrated in the catlinite quarries. In other NPS units, 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.

Potential Resource Management Actions

The Geologic Resources Division provides technical and policy support for geologic resource management issues surrounding geologic heritage, active processes and hazards, and energy and minerals management. Contact the division (http://go.nps.gov/geology) for assistance with resource inventories, assessments and monitoring; impact mitigation, restoration, and adaptation; hazards risk management; law, policy, and guidance; resource management planning; data and information management; and outreach and youth

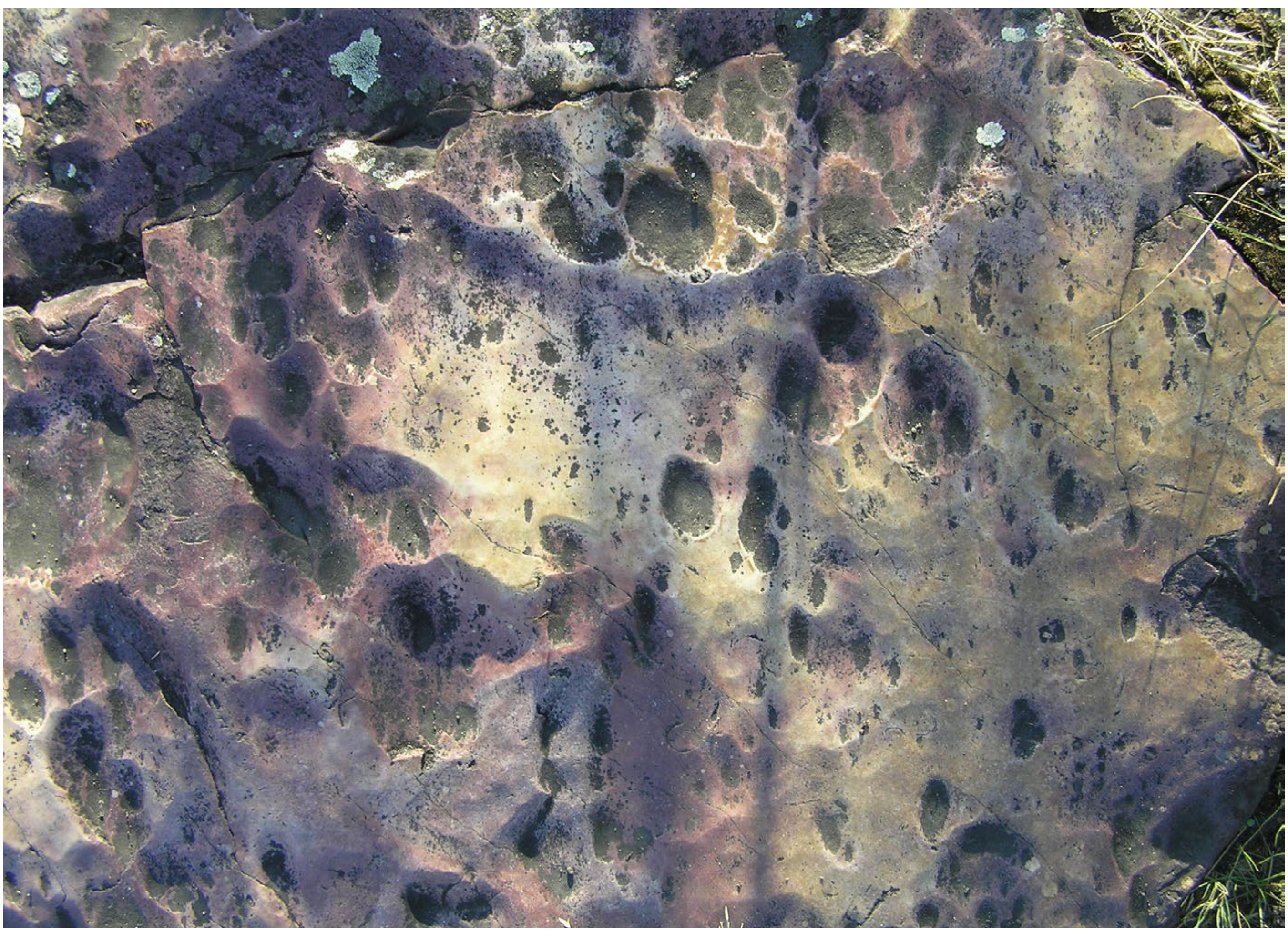


Figure 10. Photograph of polished and pitted surface of the Sioux Quartzite. Wind-blown sand polished and pitted this outcrop. Such features are called "ventifacts." Photograph courtesy of Mark Jirsa (Minnesota Geological Survey).

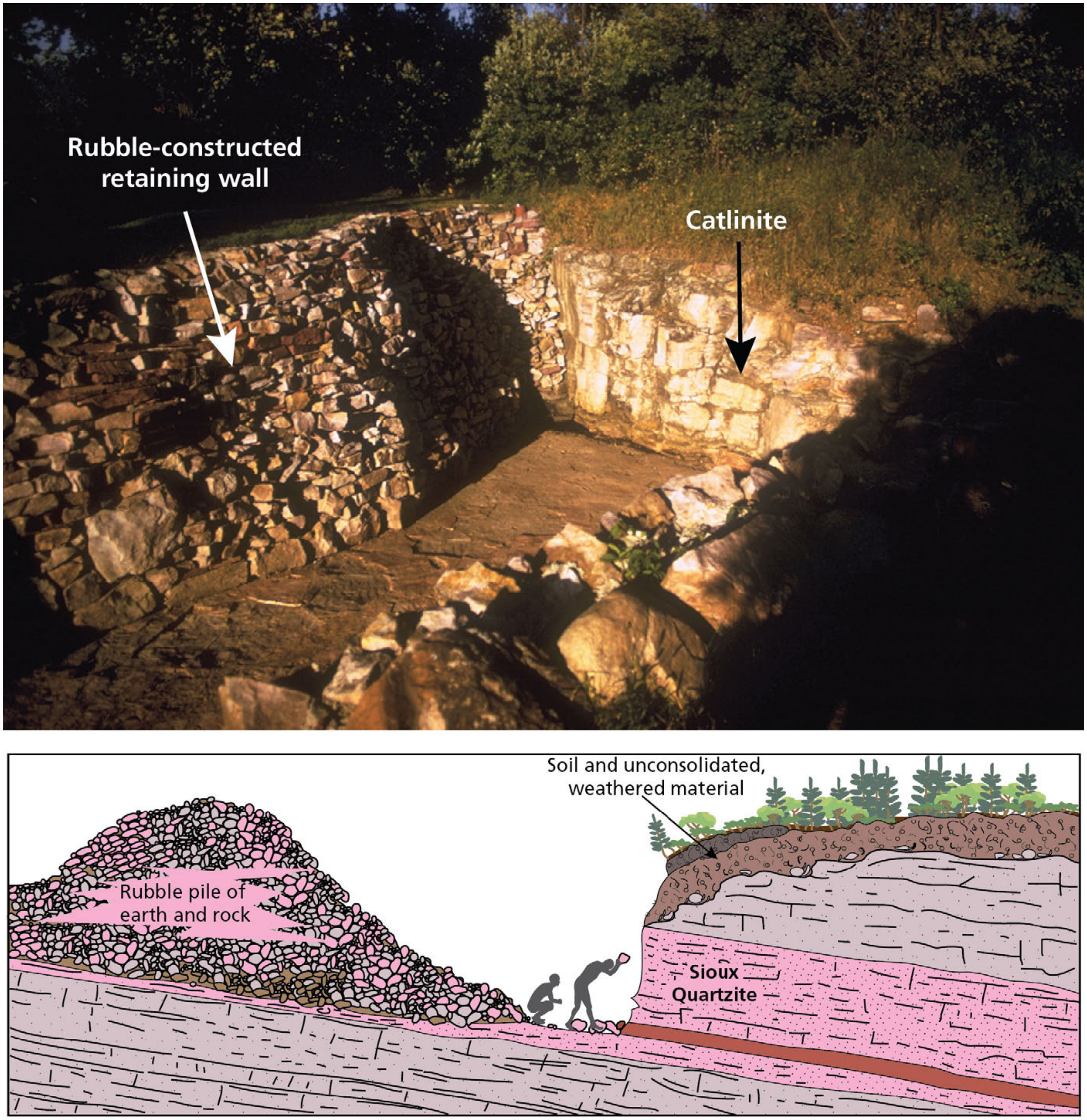


Figure 11. Photograph and schematic illustration of Sioux Quartzite quarry at Pipestone National Monument. Catlinite, or pipestone, forms reddish layers between the fractured slabs of quartzite. The schematic illustrates quarrying operations. Potential rockfall in the quarries poses a safety hazard in the monument. National Park Service photograph. Schematic redrafted by Trista Thornberry-Ehrlich (Colorado State University) after NPS graphic available from https://www.nps.gov/pipe/learn/historyculture/images/quarrydrawing556x200_2.jpg (accessed 29 July 2016).

programs (Geoscientists-in-the-Parks and Mosaics in Science).

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

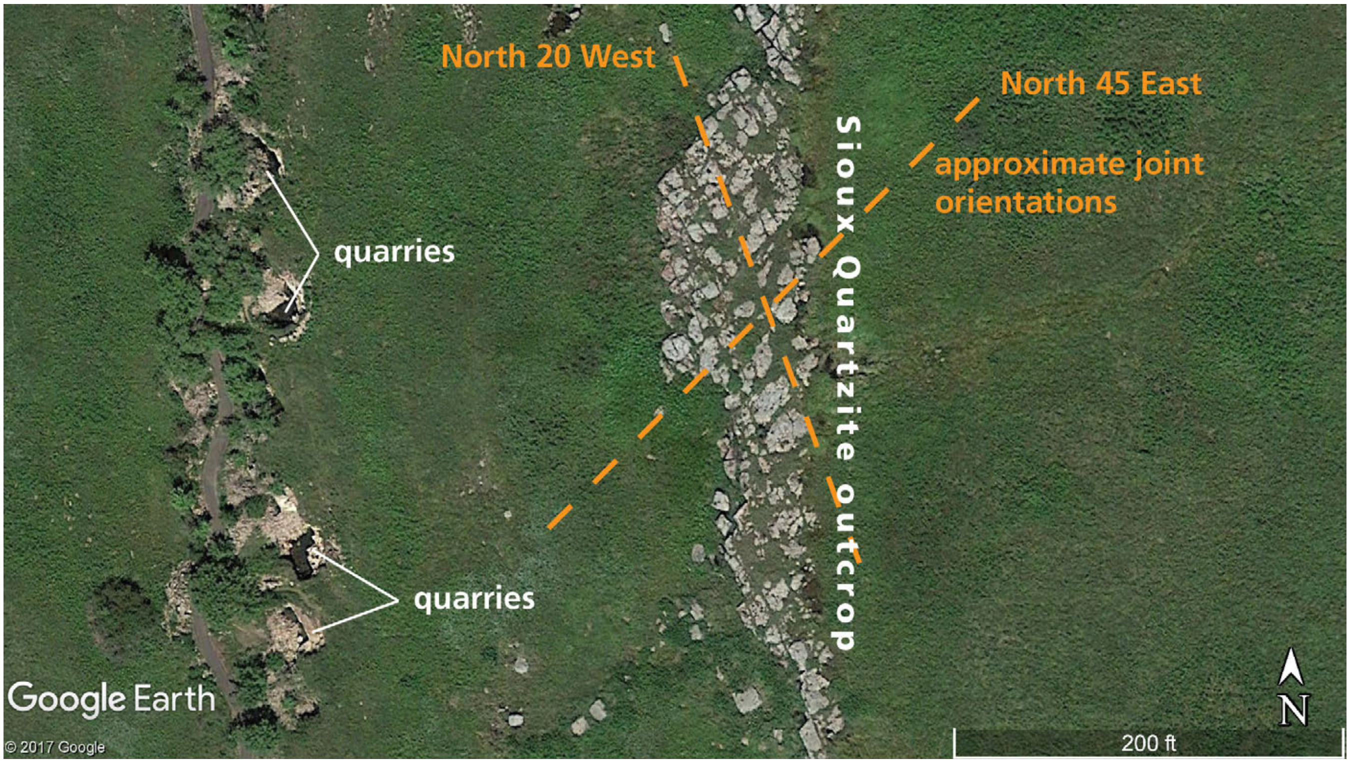


Figure 12. Aerial imagery of jointed outcrops of Sioux Quartzite and quarries in Pipestone National Monument. Note the similar orientation of the quarries to the joints. Quarries were excavated to take advantage of the joints as it is easier to remove rock along existing fractures (joints) than attempt to break through solid rock. The exposures and quarries in the image are located about 260 meters (285 yards) southeast of the visitor center. Google Earth imagery © 2017 Google. Annotations by Jason Kenworthy (NPS Geologic Resources Division) using information from Mark Jirsa (geologist, Minnesota Geological Survey, written communication, 17 March 2017).

covers a different geologic resource and includes detailed recommendations for resource managers, suggested methods of monitoring, and case studies.

The Geoscientists-in-the-Park and Mosaics in Science programs are internship programs to place scientists (typically undergraduate students) in parks to complete geoscience-related projects that may address resource management issues. Projects at Pipestone National Monument have included (as of March 2016):

- Inventory and monitoring (2011)
- Research (2009)
- Interpretation and education (2002).

Projects are listed on the GIP website: http://go.nps.gov/gip (accessed 19 April 2016). Products created by the program participants may be available on that website or by contacting the Geologic Resources Division.

Flooding

Part of the preferred alternative in the park's General Management Plan includes removal of the visitor center and parking lot from near Pipestone Creek (National Park Service 2008). These alterations to the landscape will improve water flow through the monument and reduce the damage that flooding has on park infrastructure. As documented in the General Management Plan, park managers should consult NPS planning documents including Director's Orders 77–1 (Wetland Protection) and 77–2 (Floodplain Management), associated Executive Orders, NPS Management Policies (2006), as well as the other laws, regulations, and policies listed in Appendix B and available at https://www.nps.gov/applications/npspolicy/index.cfm (accessed 29 March 2016).

If the park management desires quantitative information regarding rates of change and channel morphology of Pipestone Creek, repeat photography

Figure 13. Photograph of flood waters inundating the Circle Trail in 2010. Alterations to the landscape proposed in the Final General Management Plan (National Park Service 2008) should alleviate the impact of flooding on monument infrastructure. National Park Service photograph available online: http://www.nps.gov/pipe/learn/photosmultimedia/index.htm (accessed 26 August 2015).

could be performed at designated photo points to monitor changes. Refer to http://go.nps.gov/grd_photogrammetry for information about using photogrammetry for resource management.

Quarries may also flood during or after significant precipitation and when groundwater levels are high (fig. 13). Park staff may utilize pumps to remove water and provide access to the quarries.

Flooding will likely be more of an issue as climate continues to change. According to Monahan and Fisichelli (2014), current climate conditions at Pipestone National Monument have already started to shift beyond the 1901–2012 historical range of temperature and precipitation variability. Not only will average temperature and precipitation conditions change but also particular extreme climate events such as intense storms, flooding, and drought are projected to increase (Monahan and Fisichelli 2014). Extreme climate events may cause shifts in the conditions of Pipestone Creek, the quarries, and other park resources that may affect visitor experience.

Extreme rainfall events and flooding caused by regional climate in the Midwest and Great Plains are expected to increase erosion, cause water quality to decline, and negatively impact transportation, agriculture, human health, and infrastructure (Pryor et al. 2014). Frequent extreme events in an already highly variable climate system will especially stress communities that are already vulnerable to weather and climate extremes (Shafer et al. 2014). The NPS Climate Change Response Program (https://www.nps.gov/orgs/ccrp/index.htm) provides additional information regarding climate change, its effects on park resources, and adaptation procedures for park managers.

Rockfall and Quarry Use

Hard, fractured rock such as the Sioux Quartzite naturally breaks into large blocks. Quarriers utilize this characteristic to facilitate removal of the quartizite. These processes are natural elements of landscape change, but they become hazards when visitors hike near the base of cliffs or in quarries. Areas with visible cracks, loose material, or overhangs become particularly hazardous. Alerting visitors and quarriers to the hazards

Figure 14. Photograph of water in a quarry. Seasonal flooding may inundate the quarries at Pipestone National Monument. Water entering the quarries may be contaminated. Once the water is pumped out of the quarries and the quarries dry out, the dust may contain those contaminants. National Park Service photograph by Jeff Rosenthal.

associated with rockfall near the base of cliffs or quarry highwalls 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 possible technique to obtain these data. The Geoscientist-in-the-Parks program (http://go.nps.gov/gip; accessed 14 March 2016) is an option to support such a project. The NPS Geologic Resources Division Photogrammetry website (http://go.nps.gov/grd_photogrammetry) 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:

- In the *Geological Monitoring* chapter about slope movements, Wieczorek and Snyder (2009) described five vital signs for understanding and monitoring slope movements: (1) types of landslide, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessment of landslide hazards and risks.
- US Geologic Survey publication T*he landslide handbook—A guide to understanding landslides* (Highland and Bobrowsky 2008).
- US Geological Survey landslides website (http://landslides.usgs.gov/).

- NPS Geologic Resources Division Geohazards website (http://go.nps.gov/geohazards).
- NPS Geologic Resources Division Slope Movement Monitoring website (http://go.nps.gov/monitor_slopes).

The high walls and rubble piles in the quarries are particularly susceptible to rock fall. Because the catlinite beds slope downward into the cliff, more overburden must be removed as quarrying continues and wall height increases, thus amplifying the risk of rockfall. Quarrying operations must follow guidelines outlined in the permit and those guidelines include basic safety information. More information may be obtained from the park's quarry permit and quarrying websites and by contacting the park for up-to-date regulations.

If any of the quarries are considered abandoned, they should be documented as part of the NPS Abandoned Mineral Lands (AML) database. Currently there are no AML features documented in Pipestone National Monument. Burghardt et al. (2014) and http://go.nps.gov/grd_aml contain information about AML in the National Park System, as well as a comprehensive inventory of sites, features, and mediation needs. The quarries at Pipestone National Monument have additional management considerations because they are also cultural resources.

Geologic History

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

2.6 billion to 1.6 billion years ago (Precambrian): Continental Collisions and River Systems.

Much of the bedrock in southwestern Minnesota, including the exposures in Pipestone National Monument, consists of Precambrian rocks more than one billion years old. Because a veneer of glacial drift covers the bedrock throughout most of Minnesota, bedrock is generally defined through remote sensing techniques such as magnetic and gravity surveys, the few surface exposures, and archived water well data and drill core data collected during exploration for uranium, oil, and metallic mineral resources (Mark Jirsa, Minnesota Geological Survey, geologist, personal communication, 19 August 2008).

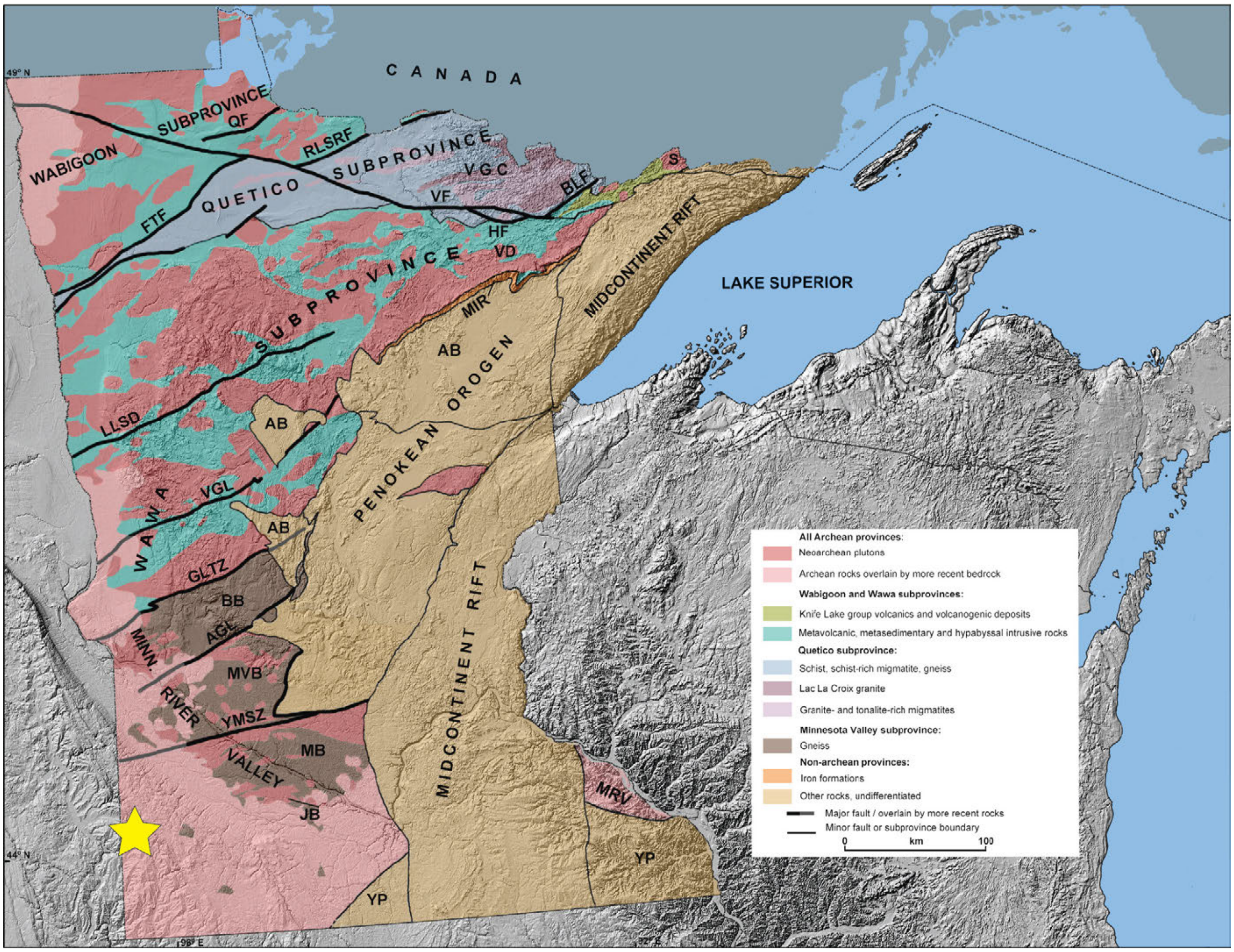


Figure 15. Map of Precambrian land masses that sutured together to form Minnesota approximately 2.7 billion to 2.5 billion years ago. In southwestern Minnesota, the Great Lakes Tectonic Zone (GLTZ) marks the contact between the Wawa Subprovince and the Minnesota River Valley Subprovince. The Minnesota River Valley contains four distinct regions separated by faults and shear zones. From north to south, these are the Benson Block (BB), the Montevideo Block (MVB), the Morton Block (MB), and the Jeffers Block (JB). The Appleton Geophysical Lineament (AGL) and Yellow Medicine Shear Zone (YMSZ) separate the blocks. Yellow star indicates location of Pipestone National Monument. Map compiled by Patrick J. Mangou from US Geological Survey and Minnesota Geological Survey sources, available at http://usgeologymorphology.com/MN-archean-p2.html (accessed 20 February 2017).

Figure 16. Paleogeographic map of North America during the last glacial maximum. Continental ice sheets advanced from the northern latitudes, and alpine glaciers formed in the mountains. During the maximum extent of the recent glaciation, about 15,000 to 12,000 years ago the ice sheet divided into two lobes that flowed around present-day Pipestone National Monument (green star), forming the Coteau des Prairies. The yellow lines denote the equator, 30°N, and 60°N latitude. Basemap is from "North American Key Time Slices" © 2013 Colorado Plateau Geosystems, Inc; used under license. Refer to http://deeptimemaps.com/ for additional information.

About 2.7 billion to 2.5 billion years ago during the Algoman Orogeny (the Kenoran Orogeny in Canada), a series of plate tectonic events accreted extensive segments of the crust, including offshore sediments, volcanic island arcs, and micro continents, onto the proto-North American continent. In southwestern Minnesota, the northeast–southwest trending Wawa Subprovince accreted to the Superior Province and the Minnesota River Valley Subprovince accreted to the Wawa Subprovince. The Great Lakes Tectonic Zone separates the two subprovinces (fig. 15).

The Minnesota River Valley Subprovince contains four distinct regions. From north to south, these are the Benson Block, the Montevideo Block, the Morton Block, and the Jeffers Block. The blocks are bordered by lineaments, which are linear features on Earth's surface, such as a fault. The Appleton Geophysical Lineament marks the border between the Benson and Montevideo blocks, and the Yellow Medicine Shear Zone separates the Montevideo Block from the Morton Block (fig. 15). Rocks in the Minnesota River Valley Subprovince include 3.5 billion year old metamorphic gneisses that were intruded by 2.5 billion year old granites.

Approximately 1.85 billion years ago, the Penokean Orogeny deformed both the Wawa and Minnesota River Valley subprovinces. About 1.0 billion years ago, the Mid-Continent Rift cut through both subprovinces. A similar continental rift is active today along the East African Rift system. The Mid-Continent Rift, however, did not fully split apart the continent, and to most geologists, the Mid-Continent Rift became known as an example of a "failed" rift system.

Approximately 1.76 billion to 1.60 billion years ago, a series of depositional basins developed on a barren continent (terrestrial plants and animals would not evolve for hundreds of millions of years) and received sediments that would eventually become the Sioux Quartzite. Similar to many other mid-continent Paleoproterozoic quartzites, the well-sorted Sioux Quartzite consists of about 90% quartz. Sedimentary features such as current-formed ripple marks, mudcracks resulting from desiccation, and trough cross-bedding (fig. 6) indicate that Paleoproterozoic streams flowed to the south, depositing sands and gravels in a braided stream environment. Without stabilizing vegetation to help check erosion, many bars or islands developed in the shifting channels in order to accommodate the massive sediment supply (Morey 1981; Morey and Setterholm 1987).

Periodic flooding deposited the fine-grained clay and silt that became Pipestone National Monument catlinite. The dynamic, turbulent, high energy flow of braided streams typically keeps these finer grained sediments suspended in the water column and transports the material out of the system. However, rapid burial preserved the isolated lenses of overbank and floodplain deposits in the Pipestone National Park area.

The past 2.6 million years (Quaternary Period): The Ice Ages

During the early and middle Pleistocene (about 2.6 million years ago to 500,000 years ago), continental glaciers flowed across Minnesota as far south as

Figure 17. Oblique aerial imagery of Pipestone National Monument and vicinity. The north–south-trending Sioux Quartzite ridge formed by glacial processes is easily visible. Google Earth map. Imagery © Landsat/Copernicus.

Missouri, and upon melting, left thick deposits of glacial debris (till) (Mickelson and Colgan 2004; Roy et al. 2004; Bettis III et al. 2010). The Wisconsin Glacial Episode, which ended about 11,000 years ago, records the most recent advance of continental glaciers into Minnesota (fig. 16).

About 14,000–12,000 years ago, the Des Moines Lobe of the Laurentide Ice Sheet advanced into southwestern Minnesota, covering older glacial drift deposited approximately 575,000 years before present (Mark Jirsa, personal communication, 19 August 2008). The Des Moines Lobe split into two lobes, which flowed to either side of the triangle-shaped Coteau des Prairies (fig. 3). Tills on the Coteau, therefore, are older than tills left by the Des Moines Lobe, and may be some of the oldest till deposits in North America (Graham 2009; Mark Jirsa, Minnesota Geological Survey, geologist, personal communication, 19 August 2008).

Glaciers left their mark on the bedrock and landscape of Minnesota. As the glaciers flowed over the Sioux Quartzite, pieces of bedrock were picked up and transported in the ice, sculpting the north–south ridge of quartzite that now bisects the monument (fig. 17). Erosional features, such as scour marks, striations, chatter marks, and wind-polished surfaces (ventifacts and pits) (fig. 10), document the battering and gouging effects that the rocks encased in ice at the base of the glacier had on the bedrock. The glaciers transformed previously deposited till into smooth rolling hills and plains. Glacial erratics, such as The Three Maidens, were left behind when the ice melted (fig. 9).

The glaciers ground sediment and rock into very fine particles that were picked up by the wind and spread across Minnesota. These eolian deposits of windblown silt (loess) blanket the till deposits in Pipestone National Monument.

Since the glaciers melted, extensive drainage systems have developed in Minnesota. Pipestone Creek flows through Pipestone National Monument and is a tributary of the Big Sioux River, which in turn flows into the Gulf of Mexico via the Missouri and Mississippi rivers. River deposited sediment (alluvium) mark the present, as well as abandoned, drainage systems.

Geologic Map Data

A geologic map in GIS format is the principal deliverable of the GRI program. GRI GIS data produced for the park follows the source maps listed here and includes components described in this chapter. A poster (in pocket) displays the data over imagery of the monument and surrounding area. Complete GIS data are 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.

Source Maps

The GRI team digitizes paper maps and converts digital data to conform to the GRI GIS data model. The GRI GIS data set includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, cross sections, figures, and references. The following source maps were used in creating the digital geologic map for Pipestone National Monument:

- Morey, G. B. 1983. Evaluation of catlinite resources, Pipestone National Monument, Minnesota. Research/Resources Management Report MWR-4. National Park Service, Midwest Region, Omaha, Nebraska.
- National Park Service, Midwest Region Field Area. 1997. Pipestone County Soil Survey (scale 1:6,000). Unpublished. National Park Service, Midwest Region, Omaha, Nebraska.
  This digital data set was derived from the Pipestone County Soil Survey by the Soil Conservation Service (Hokanson et al. 1976).

Conversion of Source Maps to GRI GIS Data

The Morey (1983) data were not in a geospatially referenced format. The GRI team derived the GRI GIS data from figures in the report and georeferenced them using geographic points with accurately georeferenced US Geological Survey base maps in ArcGIS. The Morey (1983) map only showed the extent of Sioux Quartzite (**PCsq**). The outcrop layer, derived from another figure in Morey (1983), does not overlap all exposures visible in aerial imagery (e.g., Google Earth). A future mapping project could be to document all exposures and quarries on the ground. A Geoscientist-in-the-Parks or Mosaics In Science intern could assist this project, which could be part of "inventories 2.0." Contact NPS Geologic Resources Division for additional information.

To approximate the extent of Quaternary deposits, the GRI team derived geologic units from source materials of soils on the county soil survey map. Additional information regarding the derived units, as well as the original figures from Morey (1983), are compiled in the GRI GIS data (pipe_geology.pdf).

GRI GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is available at http://go.nps.gov/gridatamodel. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for the park using data model version 2.1. The GRI Geologic Maps website, http://go.nps.gov/geomaps, provides more information about GRI map products.

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

The following components are part of the GRI GIS data set:

- A GIS readme file (pipe_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information.
- Data in ESRI geodatabase GIS format;
- Layer files with feature symbology (table 4);
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information document (pipe_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures; and
- An ESRI map document (pipe_geology.mxd) that displays GRI GIS data

Geologic Map Poster

A poster of the GRI GIS data draped over aerial imagery of the park and surrounding area is included with this report (in pocket). Not all GIS feature classes are included on the poster (table 4). Geographic information and selected park features have been added to the posters. Contact GRI for assistance locating these data.

Use Constraints

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

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features on the poster. Based on the source map scale (1:6,000) and US National Map Accuracy Standards, geologic features represented in the geologic map data are horizontally within 3 m (10 ft) of their true locations. Refer to the "Conversion of Source Maps" section for additional information about relationship of GRI GIS data to bedrock exposures in the park.

Table 4. GRI GIS data layers for Pipestone National Monument.

Data Layer	On Poster?
Geologic Cross Section Lines	No
Geologic Attitude Observation Localities (strike and dip, paleocurrent direction, axial trace of bedding surface, strike of ripple marks)	No
Mine Point Features (drill holes for "lithic logs" in pipe_geology.pdf)	No
Generalized Bedding Trends	No
Topographic Lineaments	No
Mine Area Feature Boundaries (quarries)	Yes
Mine Area Features (quarries)	Yes
Linear Geologic Units (catlinite beds)	Yes
Outcrop Boundaries (Sioux Quartzite)	Yes
Outcrops (Sioux Quartzite)	Yes
Derived Geologic Unit Boundaries (derived from soil survey)	Yes
Derived Geologic Units (derived from soil survey)	Yes

Literature Cited

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

Allen, J. R. L. 1965. A review of the origin and characteristics of recent alluvial sediments. Sedimentology 5:89–191.

Berg, E. L. 1938. Notes on catlinite and the Sioux Quartzite. American Mineralogist 23:258–268.

Bettis III, E. A., S. Tassier-Surine, and D. J. Quade. 2010. Quaternary geology of the Iowa City area. Pages 143–161 *in* T. Marshall and C. L. Fields, editors. The geology of Klein and Conklin quarries, Johnson County, Iowa. Guidebook 87. Geological Society of Iowa, Iowa City, Iowa.

Bierman, P. R., K. A. Marsella, C. Patterson, P. T. Davis, and M. Caffee. 1999. Mid-Pleistocene cosmogenic minimum-age limits for pre-Wisconsinan glacial surfaces in southwestern Minnesota and southern Baffin Island: a multiple nuclide approach. Geomorphology 27: 25–39.

Boszhardt, R. F., and J. N. Gundersen. 2014. X-ray powder diffraction analysis of Early and Middle Woodland red pipes from Wisconsin. Midcontinental Journal of Archaeology 28(1):33–48.

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. http://go.nps.gov/aml_publications (accessed 24 August 2015).

Diamond, D. D., L. F. Elliott, M. D. DeBacker, K. M. James, D. L. Pursell, and A. Struckhoff. 2014. Vegetation mapping and classification of Pipestone National Monument, Minnesota: Project report. Natural Resource Report NPS/PIPE/NRR—2014/802. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2209418 (accessed 26 July 2016).

Emerson, T. E., and R. E. Hughes. 2001. De-mything the Cahokia catlinite trade. Plains Anthropologist 46(175):149–161.

Emerson, T. E., R. E. Hughes, K. B. Farnsworth, S. U. Wisseman, and M. R. Hynes. 2005. Tremper Mound, Hopewell catlinite and PIMA technology. Midcontinent Journal of Archaeology 30(2):189–216.

Graham, J. 2009. Geologic Resources Inventory Scoping Summary: Pipestone National Monument, Minnesota. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs (accessed 25 August 2015).

Gundersen, J. N. 1982. Triclinic pyrophyllites of Kansas and Minnesota pipestones. Geological Society of America Abstracts with Programs 14 (3):112.

Gundersen, J. N. 1984. Provenance analysis of plains pipestone argillites. Geological Society of America. Abstracts with Programs 16(6):526.

Gundersen, J. N. 1987. Wisconsin pipestone: a preliminary mineralogical examination. The Wisconsin Archeologist 68:1–21.

Gundersen, J. N. 1988. Pipestones of the St. Helena Phase. Pages 79–97 *in* D. Blakeslee, editor. St. Helena Archaeology: New Data, Fresh Interpretations. J & L Reprint Company, Lincoln, Nebraska.

Gundersen, J. N. 1991. The mineralogical characterization of catlinite from its sole provenance. National Park Service, Midwest Region, Lincoln, Nebraska. Research/Resource Management Report MWR 17.

Gundersen, J. N. 1993. Catlinite and the spread of the Calumet Ceremony. American Antiquity 58:56–62.

Gurney, G. and T. T. Heyman, editors. 2002. George Catlin and his Indian Gallery. Smithsonian American Art Museum, Washington, DC and W. W. Norton and Company, New York, New York.

Highland, L. M., and P. Bobrowsky. 2008. The landslide handbook–a guide to understanding landslides. US Geological Survey Circular 1325. https://pubs.usgs.gov/circ/1325/ (accessed 1 June 2017).

Hofmann, B.A. 1991. Mineralogy and petrology of reduction spheroids in red beds: Mineralogy and Petrology, v. 44, p. 107-124.

Hokanson, H. L., F. D. Lorenzen, J. J. Murray, and R. O. Paulson. 1976. Soil survey of Pipestone County, Minnesota. Soil Conservation Service (National Cooperative Soil Survey), St. Paul, Minnesota. https://www.nrcs.usda.gov/Internet/FSE_MANUSCRIPTS/minnesota/MN117/0/Pipestone_MN.pdf (accessed 28 August 2017).

Hunt, R., J. P. Kenworthy, and V. L. Santucci. 2008. Paleontological resource inventory and monitoring—Heartland Network. Natural Resource Technical Report NPS/NRPC/NRTR—2008/132. National Park Service, Fort Collins, Colorado.

Jacob, J. M. 2005. The Washington Monument: a technical history and catalog of the commemorative stones. National Park Service, Northeast Region Design, Construction, and Facility Management Directorate, Architectural Preservation Division. https://www.nps.gov/parkhistory/online_books/wamo/stones.pdf (accessed 28 August 2017).

Jirsa, M., C. Jennings, A. Watson, and N. Meyer. 2015. Geology of Blue Mounds State Park. Minnesota Department of Natural Resources Contract #93015. Minnesota Geological Survey, Minneapolis, Minnesota. ftp://ftp.gisdata.mn.gov/pub/gdrs/data/pub/us_mn_state_dnr/geos_blue_mounds_state_park/metadata/BMgeology.pdf (accessed 30 July 2016).

Jones, J. V., III, J. N. Connelly, K. E. Karlstrom, M. L. Williams, and M. F. Doe. 2009. Age, provenance, and tectonic setting of Paleoproterozoic quartzite successions in the southwestern United States. Geological Society of America Bulletin 121:247–264.

Jones, D. S., R. Cook, J. Sovell, C. Herron, J. Benner, K. Decker, S. Sherman, A. Beavers, J. Beebee, and D. Weinzimmer. 2016. Pipestone National Monument natural resource condition assessment. Natural Resource Report NPS/PIPE/NRR—2016/1106. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2226138 (accessed 3 August 2016).

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://go.nps.gov/geomonitoring (accessed 24 April 2017).

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://go.nps.gov/geomonitoring (accessed 28 March 2017).

Medaris, L.G., Jr., B. S. Singer, R. H. Dott, Jr., A. Naymark, C. M. Johnson, and R. C. Schott. 2003. Late Paleoproterozoic climate, tectonics, and metamorphism in the southern Lake Superior region and proto-North America: Evidence from Baraboo interval quartzites. Journal of Geology 111:243–257.

Miall, A. D. 1992. Alluvial deposits. Pages 119–142 in R. G. Walker and N. P. James, editors. Facies models: response to sea level change. Geological Association of Canada, Memorial University of Newfoundland, St. John's, Newfoundland, Canada.

Mickelson, D. M., and P. M. Colgan. 2004. The southern Laurentide Ice Sheet. Pages 1–17 *in* A. R. Gillespie, S. C. Porter, and B. F. Atwater, editors. The Quaternary Period in the United States. Developments in Quaternary Science 1. Elsevier, New York, New York.

Monihan, W. B. and N. A. Fisichelli. 2014. Recent climate change exposure of Pipestone National Monument. Climate Change Resource Brief. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2214016 (accessed 19 April 2016).

Morey, G. B. 1981. Evaluation of catlinite resources, Pipestone National Monument, Minnesota. Open-File Report OFR 81–02. Minnesota Geological Survey, St. Paul, Minnesota. http://conservancy.umn.edu/handle/11299//122274 (accessed 25 August 2015).

Morey, G. B. 1983. Evaluation of catlinite resources, Pipestone National Monument, Minnesota. NPS Research/Resources Management Report MWR–4. National Park Service, Midwest Regional Office, Omaha, Nebraska.

Morey, G. B., and D. R. Setterholm, 1987, Pipestone National Monument: the Sioux Quartzite–an Early Proterozoic braided stream deposit, southwestern Minnesota. Centennial Field Guide–North-Central Section. Geological Society of America, Boulder, Colorado.

Morey, G. B. 1984. Sedimentology of the Sioux Quartzite in the Fulda Basin, Pipestone County, southwestern Minnesota. Report of Investigations 32. Minnesota Geological Survey, St. Paul, Minnestoa.

National Park Service. 2008. Final general management plan/environmental impact statement Pipestone National Monument. Pipestone National Monument, Pipestone, Minnesota. http://www.nps.gov/pipe/learn/management/upload/PIPE_FinalGMP_completedoc.pdf (accessed 26 August 2015).

National Park Service. 2015a. Pipestone: geologic formations. Pipestone National Monument, Pipestone, Minnesota. http://www.nps.gov/pipe/learn/nature/geologicformations.htm (accessed 25 August 2015).

National Park Service. 2015b. Pipestone: Three Maidens. National Park Service, Pipestone, Minnesota. http://www.nps.gov/pipe/learn/historyculture/three-maidens.htm (accessed 27 August 2015).

National Park Service. 2016a. Pipestone National Monument Foundation Document. Draft in review.

National Park Service. 2016b. Nature. Pipestone National Monument, Pipestone, Minnesota. https://www.nps.gov/pipe/learn/nature/index.htm (accessed 26 July 2016).

Patterson, C. J. 1995. Surficial geologic map (scale 1:200,000). Regional Hydrogeologic Assessment RHA-2, Part A. Minnesota Geological Survey, St. Paul, Minnesota. http://conservancy.umn.edu/handle/11299//59763 (accessed 26 August 2016).

Pryor, S. C., D. Scavia, C. Downer, M. Gaden, L. Iverson, R. Nordstrom, J. Patz, and G. P. Robertson. 2014. Midwest. Pages 418–440 (chapter 18) *in* J. M. Melillo, T. C. Richmond, and G. W. Yohe, editors. Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program. doi:10.7930/J0J1012N. http://nca2014.globalchange.gov/report/regions/midwest (accessed 21 February 2017).

Rothman, H. K., and D. J. Holder. 1992. Managing the sacred and the secular: an administrative history of Pipestone National Monument. Midwest Region, National Park Service Report MWR–1–0015–002. https://www.nps.gov/parkhistory/online_books/pipe/adhi.htm (accessed 26 July 2016).

Roy, M., P. U. Clark, R. W. Barendregt, J. R. Glasmann, and R. J. Enkin. 2004. Glacial stratigraphy and paleomagnetism of late Cenozoic deposits of the north-central United States. Geological Society of America Bulletin 116:30–41.

Scott, D. D., T. D. Thiessen, J. J. Richner, and S. Stadler. 2006. An archeological inventory and overview of Pipestone National Monument, Minnesota. Occasional Studies in Anthropology 34. Midwest Archeological Center, National Park Service, Lincoln, Nebraska.

Shafer, M., D. Ojima, J. M. Antle, D. Kluck, R. A. McPherson, S. Petersen, B. Scanlon, and K. Sherman. 2014. Great Plains. Pages 441–461 (chapter 19) *in* . M. Melillo, T.C. Richmond, and G. W. Yohe, editors. Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program. doi:10.7930/J0D798BC. http://nca2014.globalchange.gov/report/regions/great-plains (accessed 21 February 2017)

Southwick, D. L. 2002. Geologic map of pre-Cretaceous bedrock in southwest Minnesota (scale 1:250,000). Miscellaneous Map Series Map M–121. Minnesota Geological Survey, St. Paul, Minnesota. http://conservancy.umn.edu/handle/11299//928 (access 26 August 2015).

Truettner, W. H. 1979. The natural man observed: a study of Catlin's Indian Gallery. Smithsonian Books, Washington, DC.

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://go.nps.gov/geomonitoring (accessed 28 March 2017).

Wisseman, S. U., T. E. Emerson, R. E. Hughes, and K. B. Farnsworth. 2011. Provenance studies of Midwestern pipestones using portable infrared spectrometer. Pages 335–342 *in* I. Turbanti-Memmi, editor. Proceedings of the 37th International Symposium on Archaeometry. DOI 10.1007/978-3-642-14678-7_48. Springer-Verlag Berlin Heidelberg. https://www.researchgate.net/publication/265526794_Provenance_Studies_of_Midwestern_Pipestones_Using_a_Portable_Infrared_Spectrometer (accessed 1 August 2016).

Wisseman, S. U., R. E. Hughes, T. E. Emerson, and K. B. Farnsworth. 2012. Refining the identification of native American pipestone quarries in the midcontinental United States. Journal of Archaeological Science 39:2496–2505.

Additional References

This section lists additional references, resources, and websites that may be of use to resource managers. Web addresses are valid as of February 2017. 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—*Energy and Minerals, Active Processes and Hazards, and Geologic Heritage*: http://go.nps.gov/geology/
- NPS Geologic Resources Inventory: http://go.nps.gov/gri
- NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program: http://go.nps.gov/gip
- NPS Views program (geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a variety of geologic parks): http://go.nps.gov/views

NPS Resource Management Guidance and Documents

- 1998 National Parks Omnibus Management Act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf
- Geologic monitoring manual: http://go.nps.gov/geomonitoring
- 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/
- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://www.nps.gov/dsc/technicalinfocenter.htm http://etic.nps.gov/

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

- Minnesota Geological Survey: http://www.mngs.umn.edu/
- US Geological Survey: http://www.usgs.gov/
- USGS Publications: http://pubs.er.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

- Geologic glossary (simplified definitions): http://geomaps.wr.usgs.gov/parks/misc/glossarya.html
- 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")
- National geologic map database (NGMDB): http://ngmdb.usgs.gov/
- Publications warehouse (many publications available online): http://pubs.er.usgs.gov

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting for Pipestone National Monument, held on 19 August 2008, or the follow-up report writing conference call, held on 21 June 2016. 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.

2008 Scoping Meeting Participants

Name	Affiliation	Position
Brinkman, Josh	NPS Pipestone National Monument	Biological technician
Connors, Tim	NPS Geological Resources Division	Geologist
Graham, John	Colorado State University	Geologist
Jirsa, Mark	Minnesota Geological Survey	Geologist
Lundstrom, Scott	US Geological Survey	Geologist
Norby, Lisa	NPS Geological Resources Division	Geologist
Swanson, Landon	NPS Pipestone National Monument	Biological technician

2016 Conference Call Participants

Name	Affiliation	Position
Connors, Tim	NPS Geological Resources Division	Geologist
Graham, John	Colorado State University	Geologist, GRI report writer
Hendriks, Seth	NPS Pipestone National Monument	Biological Science Technician
Jirsa, Mark	Minnesota Geological Survey	Geologist
Kenworthy, Jason	NPS Geologic Resources Division	Geologist, GRI reports coordinator
Livermont, Glen	NPS Pipestone National Monument	Superintendent

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
Rocks and Minerals	**NPS Organic Act, 16 USC. § 1 *et seq*.** directs the NPS to conserve all resources in parks (which includes rock and mineral resources) unless otherwise authorized by law. **Exception: 16 USC. § 445c (c) – Pipestone National Monument enabling statute**. Authorizes American Indian collection of catlinite (red pipestone).	**36 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources… in park units. **Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown. **Exception: 36 C.F.R. § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, and Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
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
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.	S**ection 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 372/140095, September 2017

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

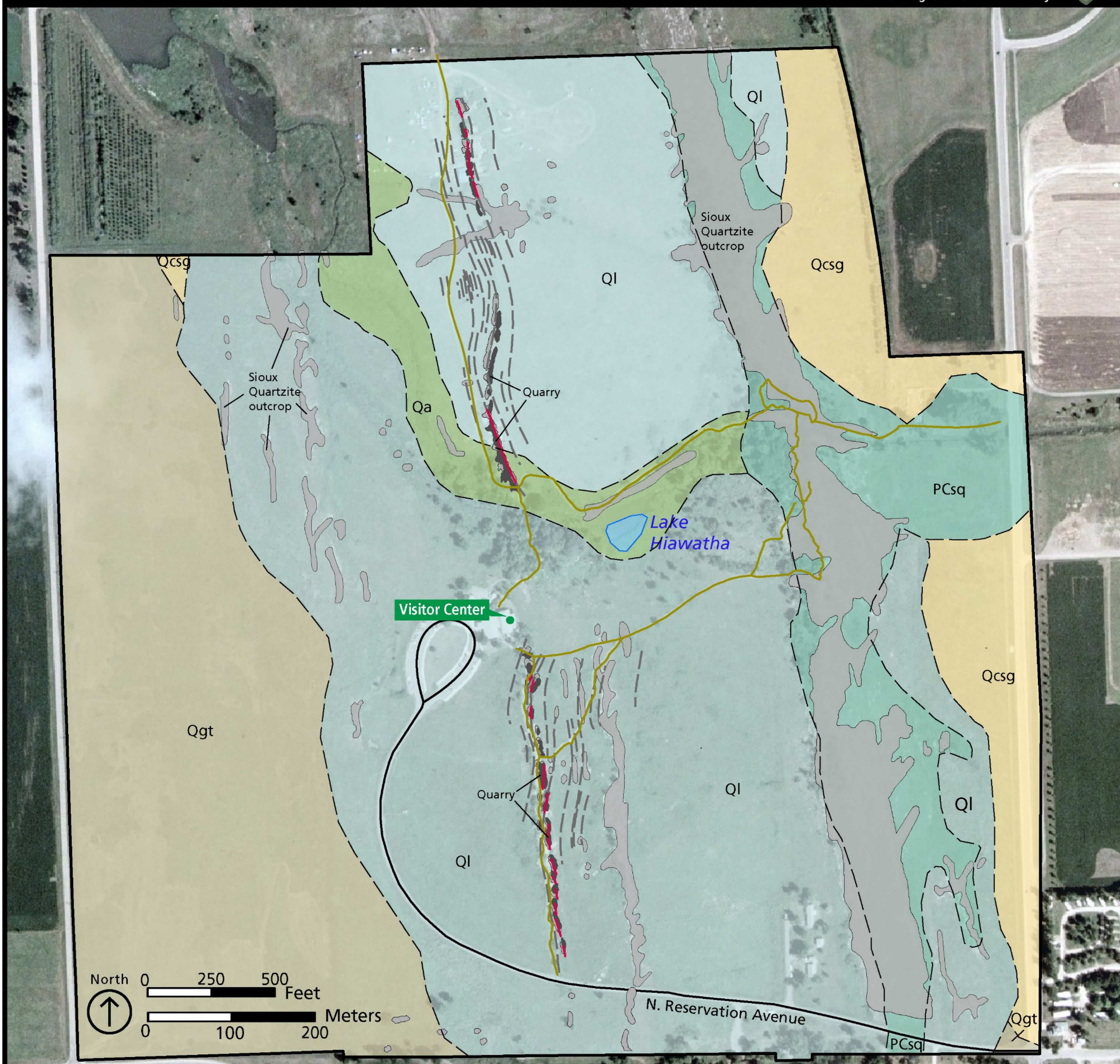
EXPERIENCE YOUR AMERICA™

Geologic Map of Pipestone National Monument

Minnesota

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory



Infrastructure

Roads

Trail

Geologic Contacts

Approximate

Linear Geologic Units

PCct - Sioux Quartzite: Catlinite beds (Early Proterozoic), known or certain

PCct - Sioux Quartzite: Catlinite beds (Early Proterozoic), inferred

Mine Area Features

Quarry

Geologic Units

Water	
Qa	Alluvium (Quaternary)
Ql	Loess (Quaternary)
Qcsg	Calcareous sand and gravel (Quaternary)
Qgt	Glacial till (Quaternary)
PCsq	Sioux Quartzite (Early Proterozoic)
	Sioux Quartzite outcrop

Location Map

This map was produced by Kari Lanphier and Georgia Hybels (Colorado State University) in August 2017. 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 are:

Morey, G.B. 1983. Evaluation of catlinite resources, Pipestone National Monument, Minnesota. Research/Resources Management Report MWR-4. National Park Service, Midwest Region, Omaha, Nebraska.

National Park Service, Midwest Region Field Area. 1997. Pipestone County Soil Survey (scale 1:6,000). Unpublished. National Park Service, Midwest Region, Omaha, Nebraska. *This digital data set was derived from the Pipestone County Soil Survey by the Soil Conservation Service (Hokanson et al. 1976).*

All Geologic Resources Inventory geologic map data and publications are available at https://go.nps.gov/gripubs.