Several quarries developed in Paleoproterozoic granite operate throughout the state, providing building stone used not only in Minnesota but also around the world, as well as crushed rock and aggregate used for railroad and highway construction. The Sioux Quartzite also is quarried for aggregate.

Mesoproterozoic Rocks

The Mesoproterozoic-age rocks are relatively unmetamorphosed compared to the other Precambrian rocks in the state. They consist mainly of gabbro and anorthosite, as well as volcanic rocks, such as basalt and rhyolite. These rocks formed around 1,100 Ma ago along the Midcontinent Rift system, a major feature that formed by the spreading apart of older continental crust. As the crust spread and thinned, fractures and faults formed; these provided pathways for molten magma from the mantle to work its way to the surface, where it erupted as volcanoes. The lava flows produced by these volcanoes are exposed along Lake Superior, and they have retained many well-preserved flow features, such as ropy tops of lava flows, which are the same as those in modern-day volcanic rocks in Hawaii. The popular Lake Superior agate, Minnesota's state gemstone, formed when vesicles (frozen gas bubbles) in these basalts were filled by thin bands of red and white quartz. The base of the volcanic pile was intruded by magma that cooled more slowly below the surface, forming gabbro, anorthosite, and granite, some of which may have supplied magmas that were erupting as lava flows higher up in the sequence. When volcanism ceased, blankets of sand—now sandstone—were deposited in a basin on top of the volcanic rocks, for example the Hinckley Sandstone exposed in Banning State Park.

Rocks similar to the Mesoproterozoic North Shore volcanic rocks were mined extensively for copper in Michigan, but no similar deposits of economic scale have been found here. In Minnesota, a large reserve of copper, nickel, and associated platinum, palladium, and gold exists at the base of the Duluth Complex, along the northwest edge of the Mesoproterozoic system, and in an intrusion near the town of Tamarack. The sandstones that overlie the volcanic rocks have been quarried in the past for building and paving stone, and gabbro and anorthosite is quarried for both dimension stone and road aggregates.

A Primer on Geology

The three basic rock groups are *igneous*, *sedimentary*, and *metamorphic*. *Igneous rocks*, which include volcanic and plutonic rocks, formed from the cooling of molten rock, or magma, that rose up from the Earth's mantle. Plutonic rocks, such as gabbro and granite, form when magma ponds in chambers deep in the Earth's crust and cools very slowly, allowing time for large crystals to form. Volcanoes form when magma from these deep chambers finds its way to the surface along fractures in the Earth's crust. Volcanic rocks are fine-grained because they cool very quickly.

Sedimentary rocks form from eroded material such as sand and mud. Graywacke is a sedimentary rock especially abundant in Minnesota that is made up of sand and mud eroded from volcanic sources.

Metamorphic rocks, such as slate, schist, and gneiss, form when a rock is recrystallized as a result of high temperature and pressure conditions found deep in the Earth's crust. The protolith, or composition of a metamorphic rock prior to recrystallization, can often be determined by the types of metamorphic minerals present. Nearly all of the rocks in the Archean and Paleoproterozoic terranes of Minnesota are technically metamorphic rocks, but the pre-metamorphic rock name is generally used to describe them.

Metamorphism typically accompanies rock deformation (folding and faulting). Rock deformation is mainly the result of a process known as plate tectonics. The hard crust of the Earth (the plate) is very thin relative to the Earth as a whole, and the Earth has several of these plates that "float" on the viscous mantle underneath. As the plates slowly drift and move relative to one another and collide, they produce some of the geologic events that we see today, such as the faults and associated earthquakes in California and the chains of volcanoes along the west coast of North and South America. Although the details of plate tectonics during Precambrian time may have differed slightly from those at present, they are overall believed to be similar. Through careful rock analysis, geologists are able to figure out the folding and faulting history preserved in the Precambrian rocks. You can see several faults on the geologic map of Minnesota; however, these are ancient faults that are no longer active.

Suggested Readings

Ojakangas, R.W., and Matsch, C.L., 1982, Minnesota's geology: Minneapolis, University of Minnesota Press, 255 p.

Morey, G.B., 1983, Geologic map of Minnesota: Bedrock geology: Minnesota Geological Survey State Map S-19, scale 1:3,000,000.

Morey, G.B., and Dahlberg, H., 1995, Geology of Minnesota: A guide for teachers: Minnesota Department of Natural Resources, 33 p.

Kesler, S.E., 2019, Great Lakes rocks: 4 billion years of geologic history in the Great Lakes region: University of Michigan Press, 368 p.

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Minnesota at a Glance

Minnesota Geological Survey
UNIVERSITY OF MINNESOTA

Precambrian Geology

What do the cliffs along the North Shore of Lake Superior, the smooth outcrops in the Boundary Waters Canoe Area Wilderness, the immense iron mines on the Mesabi Iron Range, and the knobby outcrops within the Minnesota River valley have in common? They are part of the very old bedrock that underlies all of Minnesota. Minnesota is situated at the southern edge of the Canadian Shield (Fig. 1)—the nucleus of the continent of North America that formed during Precambrian time. This period of time encompasses about 85% of Earth's history. Geologists consider Precambrian time to have begun with the formation of planet Earth about 4,550 million years (Ma) ago and to have ended about 541 Ma, when organisms with hard parts, such as shells, rapidly diversified. The rocks formed in Minnesota during this enormous span of time record a complicated geologic history that involved volcanoes, ocean islands, mountain chains, earthquakes, and unstable geologic conditions that were very different from the Minnesota of today. Precambrian Minnesota resembled modern-day Indonesia for a while; later, it resembled modern-day California; and still later it resembled parts of the Middle East and eastern Africa.

Figure 1. Extent of the Canadian Shield (gray); modified from Morey and Dahlberg (1995).

The mountains and other features of the various Precambrian landscapes were slowly eroded to low relief over many millions of years. Most of the Precambrian rocks now exposed in Minnesota's flat terrain originally were much deeper in the Earth; they record processes and conditions that existed beneath landscapes long since removed by erosion. Geologists can reconstruct the conditions that existed within the ancient Precambrian crust of the Earth through studies of these formerly deep-seated rocks now exposed at the surface. Presently, these deeply eroded Precambrian rocks are mostly covered by younger sedimentary rocks, or by a thick blanket of glacially-deposited clay, silt, sand, and gravel. However, they do appear at the surface in places in northeastern, east-central, and southwestern Minnesota.

The great span of Precambrian time is divided for convenience into two major parts—the Archean Eon (4,550-2,500 Ma) and the Proterozoic Eon (2,500-570 Ma). Each of these is divided still further (Fig. 2). The ages of rocks are determined by measuring the tiny amounts of certain naturally occurring radioactive isotopes they contain. Before isotopic dating methods were developed in the 1950s, the ages of rocks assigned to Precambrian time were not known. The igneous and metamorphic rocks beneath the younger sedimentary rocks were assigned arbitrarily to the Precambrian, without knowledge of the vast length of time they represented. The fossil-bearing rocks represent the most recent part of Earth's history, called the Phanerozoic Eon (570 Ma to present; Fig. 2).

Archean Rocks

Archean rocks make up the oldest of the Precambrian rocks, and are subdivided into two units or *terranes* (the word *terrane* indicates an area of a particular kind of rock) on the basis of their age and metamorphic history (see "A Primer on Geology" at the end of this brochure for the definition of metamorphism). All of the Archean rocks in Minnesota are part of the Superior Province of the Canadian Shield. The Superior Province is subdivided into subprovinces, which are more or less east–west, linear belts of rocks of similar geologic history and age. The subprovinces in Minnesota from south to north include the Minnesota River Valley, Wawa, Quetico, and Wabigoon.

The oldest group of Archean rocks, which are Paleoarchean to Neoarchean in age (Figs. 2, 3), is within the Minnesota River Valley subprovince. These rocks are exposed in the valley of the Minnesota River between New Ulm and Ortonville, and similar rocks underlie the southwestern quarter of the state beneath younger rocks and glacial sediment. Most of them are different kinds of gneiss (pronounced "nice"), a family of coarse-grained, streaky, or banded rocks. These gneisses have undergone multiple events of igneous intrusion and were squeezed and deformed deep in the Earth's crust like taffy, producing the banded appearance we see today. The oldest components of the gneiss are between 3,500 and 3,100 Ma in age, but later, at around 2,600 Ma, after most deformation and metamorphism had ceased, the gneiss was intruded by several large bodies

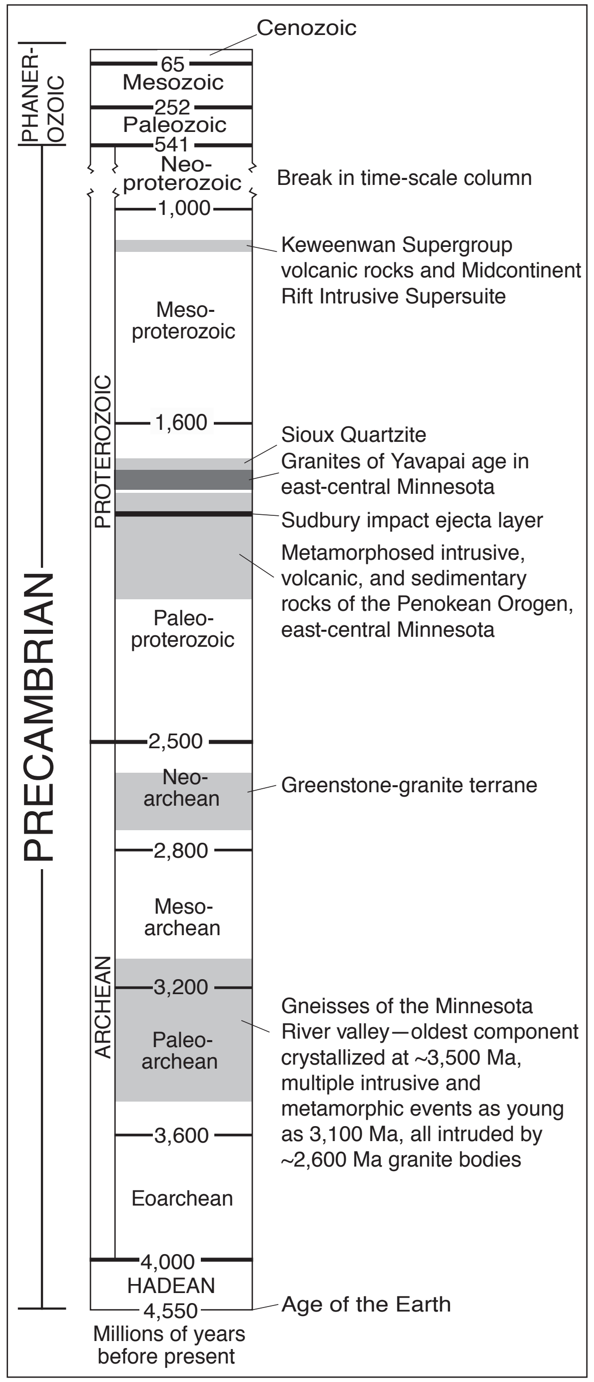

Figure 2. Geologic time scale showing ages of Precambrian bedrock in Minnesota. The ages of major Precambrian rocks units are shaded; white areas represent intervals of Precambrian time missing in Minnesota.

of granite, which have not been metamorphosed. These late granites can be seen near Fort Ridgely, south of Sacred Heart, and near Ortonville, among other places. The gneissic rocks in this continental fragment that makes up the Minnesota River Valley subprovince are about 900 million years older than the Archean volcanic rocks of northern Minnesota.

The younger Archean rocks (called *Neoarchean*) occur mainly in northern Minnesota, north of the Mesabi Iron Range, and may be seen in Voyageurs National Park, in the western part of the Boundary Waters Canoe Area Wilderness, and in scattered areas elsewhere between Lake of the Woods and Ely. This group includes the Wawa granite-greenstone subprovince, the Quetico subprovince (metamorphosed sedimentary rocks and gneiss derived from them), and the Wabigoon granite-greenstone terrane (Fig. 4). The Wawa and Wabigoon subprovinces originally were parts of volcanic chains that were later deformed and intruded by granitic rocks; the Quetico subprovince was likely a large sedimentary basin on or between those volcanic arcs. Greenstone (a dark greenish-gray, fine-grained, weakly metamorphosed basalt), metadacite (a grayish-white, fine-grained, metamorphosed volcanic rock), and graywacke (a layered gray rock made up of sand and mud eroded from volcanic sources) were the main materials in the upper parts of the Archean volcanic islands. As these volcanic chains collided they were intruded by large amounts of granite and related coarse-grained rocks that crystallized at depth from the molten state, but are now revealed at the surface by deep erosion over time. The granites welded the greenstone belts together to form an Archean continent. The Neoarchean rocks, collectively, are called the greenstone-granite terrane. The Ely greenstone is a well-known example of Neoarchean rock.

Rocks of the gneiss terrane are quarried in the Minnesota River valley for use as building stone and are also crushed for road construction and railroad ballast, among other things. Rocks of the greenstone-granite terrane are also quarried for stone, and have been extensively explored for various metals including gold, copper, zinc, lead, and iron, but no deposits worth mining have been found, except for the now-closed iron mines near Ely and Soudan. The Soudan mine is open for public tours at Lake Vermilion-Soudan Underground Mine State Park.

Proterozoic Rocks

Proterozoic rocks form two belts of very different ages and geologic histories in the eastern and central parts of Minnesota (Fig. 3). The older belt (Paleoproterozoic) crops out from St. Cloud northeast to Moose Lake and Carlton, and north up to the Mesabi Iron Range near Eveleth and Hibbing. The younger belt (Mesoproterozoic) runs along the shore of Lake Superior and continues south along the Minnesota–Wisconsin border and southwest to Kansas.

Paleoproterozoic Rocks

The southern part of the Paleoproterozoic terrane—approximately south of a line that runs west from Jay Cooke State Park (Fig. 3)—is a mixture of metamorphosed sedimentary and volcanic rocks. These were intruded later by several large granitic intrusions, emplaced between 1,800 and 1,760 Ma, which collectively form an amalgamation referred to as the East-Central Minnesota batholith (Fig. 3).

The northern part of this terrane is made up of slate and graywacke, iron formation, and quartzite. The lowest part is quartzite—formerly sandstone—that was deposited on top of the older Archean bedrock. Above the quartzite is the Biwabik Iron Formation, long mined for its vast quantities of iron ore. Slate and graywacke overlies the iron formation and covers a vast area from the Mesabi Iron Range south to Jay Cooke State Park, where one can easily see that it has been folded and deformed.

The volcanic and sedimentary rocks (now metamorphosed) that make up the southern part of the Paleoproterozoic terrane are likely part of a former mountain belt—the Penokean orogen—that extended west from Lake Huron to South Dakota, and perhaps farther, about 2,000 to 1,800 Ma ago. The eroded remnants of this belt have geologic similarities to modern mountain belts along the west coast of North America, and geologists infer that mountains comparable to those in western California existed long ago in Minnesota. During this mountain-forming orogenic event, the crust was uplifted and a large basin formed to the north; sediment shed into this northern segment produced the thick sequence of slate and graywacke in the deeper parts, and along the North Shore, the Pokegama Quartzite and Biwabik Iron Formation were deposited. The East-Central Minnesota batholith was emplaced into the southern portion during this period of uplift and crustal collision.

Slightly later in southwestern Minnesota, braided streams were flowing on an erosional surface developed on older Archean rocks within several fault-bounded basins, depositing sand layers. Later metamorphism has recrystallized the sandstone into the hard quartzite seen today in the bluffs at Blue Mounds State Park. Thin beds of reddish-brown mudstone (catlinite) in the quartzite are still being quarried—and carved—at Pipestone National Monument.

The Mesabi Iron Range (Fig. 3) is one of the largest mining districts in the world, and in 2019 the mines in Minnesota and Michigan accounted for 98% of the usable iron-ore products in the United States.

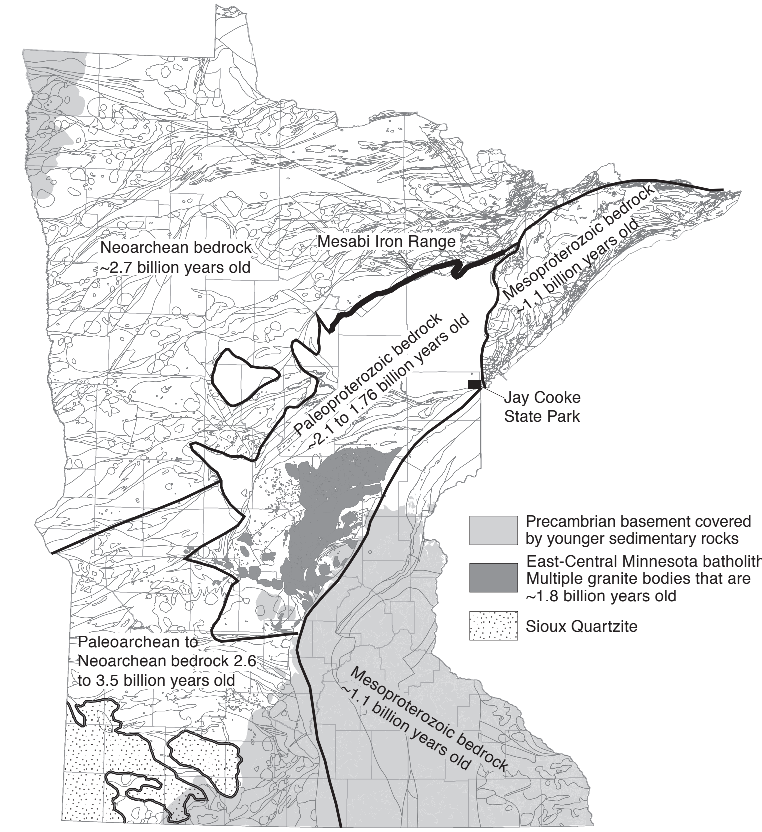

Figure 3. Geologic map of Minnesota showing the major subdivisions of the Precambrian bedrock (thick lines) and geologic unit outlines. For a complete layered bedrock geologic map see Minnesota Geological Survey Miscellaneous Maps S-21 and S-22.

Figure 4. Shaded-relief aeromagnetic image of Minnesota. This image, based on data collected in an airborne magnetic survey, shows the variable magnetic character of the rocks beneath the state. This map has no relation to ground topography. The peaks (white areas) correspond to areas where the bedrock is more magnetic and the valleys (black areas) to areas less magnetic.

Data such as these help geologists to interpret the nature of the Precambrian basement rocks because the cover of younger sedimentary rocks and glacial drift is not thick enough or magnetic enough to mask the aeromagnetic signature of the Precambrian rocks. This can be seen in the southeast, where the aeromagnetic signature of the Precambrian basement shows through Paleozoic sedimentary rocks.

The major Precambrian terranes of Minnesota are shown, separated by heavy black lines. Compare this image to the bedrock geologic map of Minnesota. Not shown on the geologic map but shown clearly on this map are a multitude of northwest-trending dikes (narrow, vertical bodies of a fine-grained equivalent of gabbro) in the northwest one-third of the state. These dikes are less than 300 feet thick, but show up well because they are strongly magnetic. Although they crop out only locally, they can be traced for miles through the use of geophysical maps such as this.