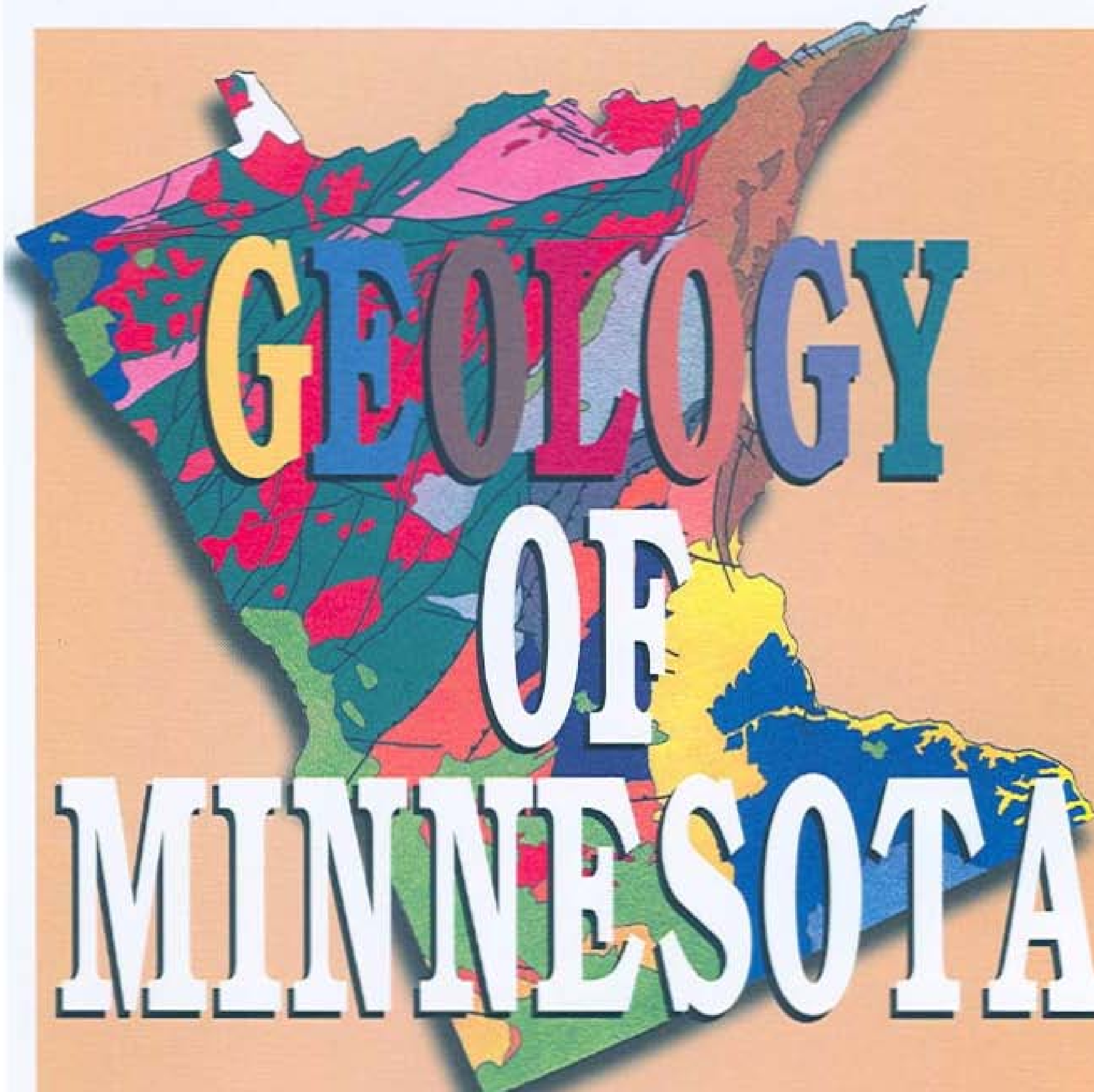

GEOLOGY OF MINNESOTA

A Guide for Teachers

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Preface

THIS BOOK WAS WRITTEN TO provide an up-to-date understanding of the geology of Minnesota to Earth Science teachers and others who have some background in geology. It is not intended to stand alone, for there are already in print many good books about rocks and other geologic phenomena in the state. These include *Minnesota's Rocks and Waters* by George M. Schwartz and George A. Thiel, first published by the University of Minnesota Press in 1954 as well as *Minnesota's Geology* by Richard W. Ojakangas and Charles L. Matsch also published by the University of Minnesota Press in 1982. A third excellent discussion is *Minnesota Underfoot* by Constance J. Sansome published by Voyager Press in 1983. Even though they are all more than 20 years old, these books, and especially the latter, remain the best guides to many of the state's outstanding geologic features.

These volumes remain useful today because the rocks at the localities described in them remain unchanged. However, research over the past decade has considerably changed our understanding of the geologic processes responsible for those geologic phenomena and their place in geologic history. Consequently many of the ideas held true in the 1980s are no longer believed today. Especially important have been the ideas of plate tectonics processes and the role they play in earth history.

Because much of the information developed recently is relatively new, it has not yet worked its way into the general literature of the state. Our goal is to summarize what geologists think today about how the rocks in Minnesota formed and their place in geologic history. We believe that if the Earth Science teachers of the state have a better understanding of the processes responsible for the major geologic phenomena, they will stimulate an interest in their students in that history and an appreciation of the varied natural surroundings.

Introduction

THE MINNESOTA WE KNOW TODAY, with its thousands of lakes, fertile farmlands, rolling southern hills, and rocky northland, started its development billions of years ago when the Earth was a new planet. Almost all aspects of our landscape—rocks, hills, valleys, rivers, lakes, peat bogs, and waterfalls—attest to that long history.

During those prehistoric times, the face of Minnesota went through many drastic changes. The rocks formed during this enormous span of time in Minnesota record a complicated history that involved volcanoes, ocean islands, mountain chains, and other geologic conditions that were very different from the Minnesota of today. Early Minnesota resembled the islands of modern-day Indonesia for a while, later it resembled the seashore of modern-day California, and still later it resembled parts of the Middle East and the rift-zone of eastern Africa. Subsequently shallow seas submerged the land and then retreated time and time again. Primitive life forms appeared, then fish, reptiles, birds, and mammals, each leaving their remains preserved in the rocks as fossils.

At times Minnesota's climate was mild or tropical. Finally the "Great Ice Age" came—about two million years ago, only yesterday by geologic time. Great glaciers advanced and retreated across Minnesota, and when the last ice had finally melted, the face of the land looked very much as it does today.

The Big Picture of Minnesota Landforms

MINNESOTA LIES NEAR the geographic center of North America (Figure 1). As such it contains the source of three great river systems. Water flows north to Hudson Bay by the Red River of the North, south to the Gulf of Mexico by the Minnesota and Mississippi rivers, and east to the Atlantic Ocean by the St. Louis River, Lake Superior, and the St. Lawrence Seaway.

A large part of the surface of Minnesota is level or gently rolling and elevations lie between 1,000 and 1,500 feet above the sea. Yet some areas have considerable relief—the geographic term for abrupt ups and downs. The distribution of these ups and downs along with streams, rivers, lakes, and other physical features of the landscape all taken together, make up what is called the topography of Minnesota (Figure 2).

Both the highest and lowest places are in the northeastern part of the state. There the surface of Lake Superior is 602 feet above sea level, but places a few miles inland from the lake reach an elevation of nearly 2,300 feet; of these, Eagle Mountain is the highest place in the state with an elevation of 2,301 feet. High ground also occurs in southwestern Minnesota and adjoining parts of South Dakota and Iowa where the Coteau des Prairies—"Highlands of the Prairies"—stands. A second conspicuous highland called the Giants Range forms a more or less continuous ridge—or narrow highland—nearly 100 miles long, extending from a few miles north of Grand Rapids in Itasca County to beyond Birch Lake in eastern St. Louis County and western Lake County. The ridge itself rises from 50 to 500 feet above the general level of the region.

Figure 1—Sketch map showing the location of Minnesota near the center of the North American Craton. The craton is that part of the North American continent underlain by rocks more than 545 million years old. Those rocks are referred to as Precambrian. Minnesota is also located near the southwestern margin of the Canadian Shield or that part of the craton where Precambrian rocks are exposed on the present land surface.

Topographically, the most rugged parts of the state are north of Lake Superior in Lake and Cook counties and in the southeast corner of the state in Houston, Fillmore, and Winona counties. Some of the prominent rock ridges along the North Shore of Lake Superior rise abruptly from 500 to 900 feet above the lake. In the southeastern counties, relief is due to an intricate natural drainage system, where streams and rivers have steep-walled valleys and ravines several hundred feet deep.

Other parts of Minnesota have very little relief and have elevations considerably less than 1,000 feet. The largest and most prominent of these is in the northwestern part of the state where some elevations in the Red River Lowland are only 760 feet above sea level.

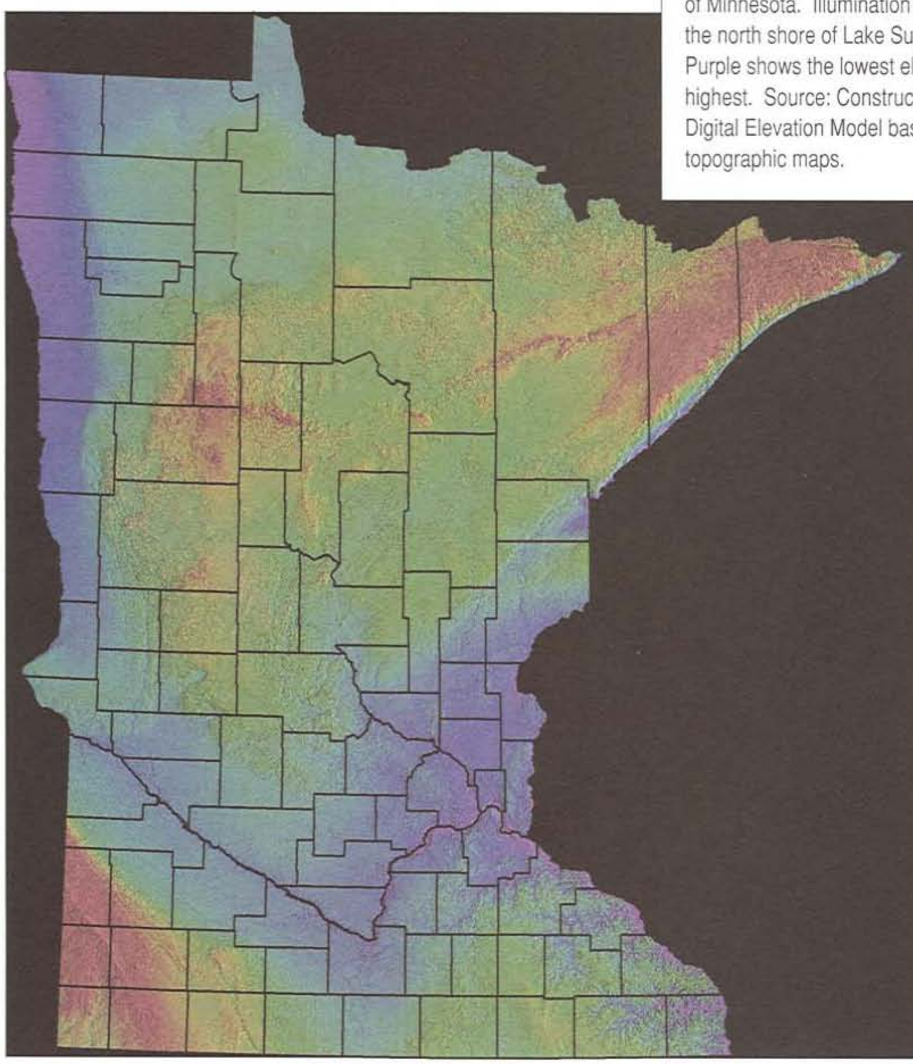


Figure 2—Colored shaded relief map of elevation of Minnesota. Illumination is from the east (so that the north shore of Lake Superior isn't in shadow). Purple shows the lowest elevation and red shows the highest. Source: Constructed from statewide USGS Digital Elevation Model based on USGS 7.5 minute topographic maps.

Maximum elevation is 2,301 feet
Minimum elevation is 590 feet

Basic Geology; Processes, Rocks, and Geologic Time

THE MAJOR UPLAND and lowland areas of Minnesota, like all land regions, are the result of many different geological processes. Rocks are important because they record processes and conditions that existed beneath landscapes long since removed by erosion. Rocks are made of minerals and rock fragments, and minerals are made of smaller units of matter—atoms—that are arranged in a regular, repetitive manner. Geologists use rocks and minerals to reconstruct geologic processes that once existed in the past.

There are many kinds of geologic processes. For example, the composition of the rocks tells us about the chemical processes that created the rocks and then changed them. Similarly, fossils contained in the rocks tell us about past biological processes and past environments. However, for the broad picture, physical or mechanical processes are the most significant.

Of the various mechanical processes, the ones most obvious to all of us involve weathering and erosion by wind, water, and temperature changes. Erosion constantly attacks our land surface, continually making small rocks out of big ones and constantly moving them down the slope of the land toward an ocean basin. The dust we see in the air, the gully formed on the hillsides, the muddy waters in the streams, and even the potholes in our streets, are all evidence that the land is being weathered and eroded away. Erosion acts to level the surface of the globe by eroding the highlands and filling up the ocean basins.

Other physical processes work to modify the landscape from below. These processes, that operate over a much longer time scale, are collectively referred to as plate tectonics—so named because the crust of the earth is broken up into seven very large segments called "plates" and numerous mid- and small-sized ones. All of the plates are moving very slowly and at widely varying rates relative to one another. Consequently, a variety of boundaries between plates can form that change considerably in length and shape over time. Figure 3 illustrates some of the components associated with moving plates. It shows that some plates are moving away from each other and are said to be divergent or spreading. The boundaries between two divergent plates are called spreading-centers or ocean ridges. They may be filled with volcanic rocks from below or sediment eroded from highlands and transported to adjacent lowlands. Other plates are moving toward each other and are said to be converging. There are two kinds of converging plate boundaries: colliding and subducting. Where two continental plates collide, the boundary is marked by uplifted high mountain chains such as the Himalayas. Where a continental plate and an oceanic

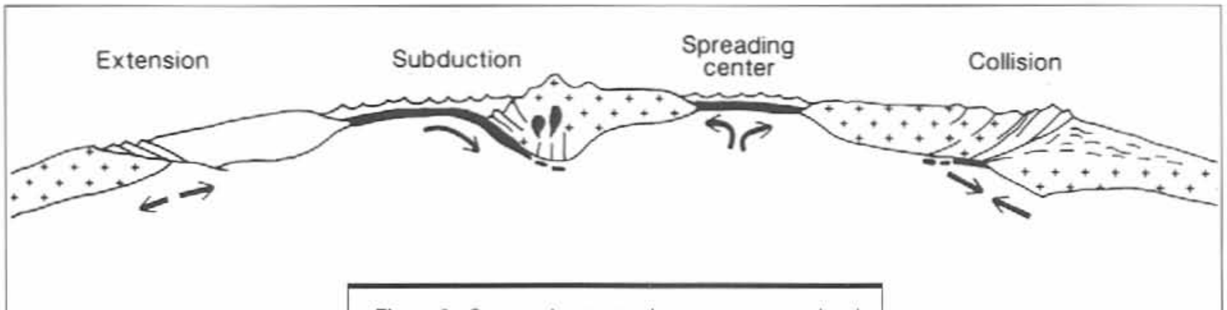


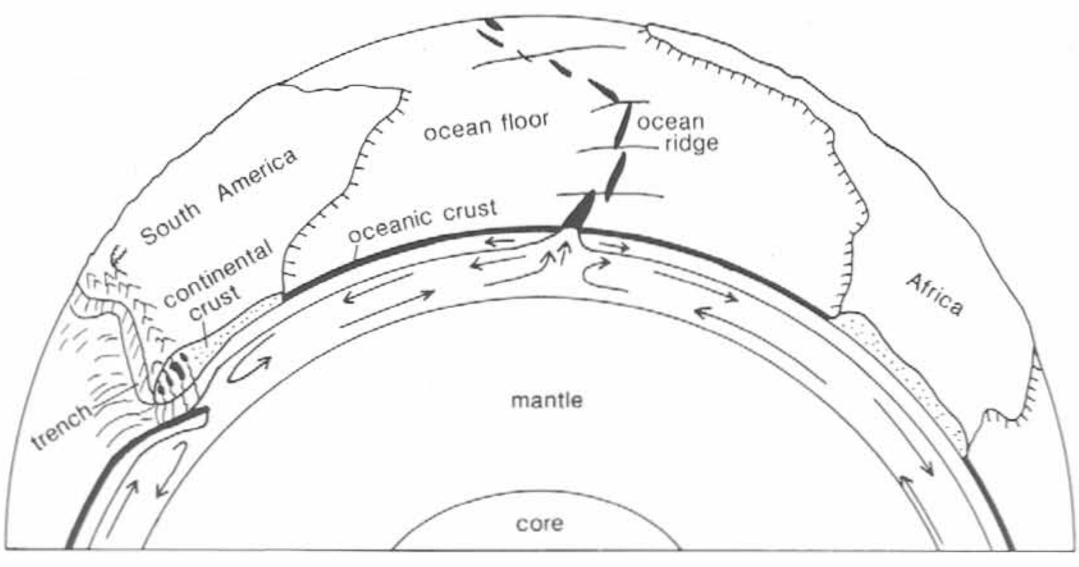
Figure 3—Some major structural components associated with plate tectonic processes.

plate collide, the oceanic plate is dragged down beneath the continental plate by a process called subduction. This boundary is marked by volcanic mountain chains such as the coastal ranges along the west coast of North America. Mount St. Helens in Washington state is one example of such a volcanic mountain. Figure 4 illustrates the present-day plate tectonic framework in the Southern Hemisphere.

Earthquakes are another result of colliding plates. Colliding plates do not always glide smoothly by one another. They stick, and after significant stress builds up, they release and suddenly surge ahead causing shock waves to pass through the Earth. We feel these shock waves as earthquakes. Thus most, but not all earthquakes are confined to the areas of plate boundaries.

Extension in the interior part of a continental plate can also produce divergence. As extension continues, the lithosphere is stretched to produce first a depression or "sag basin" (Figure 5). Continued stretching produces an elongate, an echelon rift system consisting of a series of "grabens" bounded by normal faults. The classic rift is the East African Rift System which is still undergoing extension. Figure 5 also shows that rifts represent one part of an evolutionary sequence that culminates when the lithosphere separates into two continental plates and new oceanic crust forms between them. The juncture between new oceanic crust and the fractured continental plate is called a "passive margin." Passive margins are characterized by thick sedimentary prisms very much like that found along the modern Atlantic seaboard. Geologic studies have established that extensional tectonic processes can cease and be replaced by compressional tectonic processes which leads to the ultimate collision of two plates. A complete cycle of these processes is called a "Wilson Cycle" after J. Tozo Wilson who first defined the phenomena.

Figure 4—The present-day plate tectonic framework in the Southern Hemisphere.



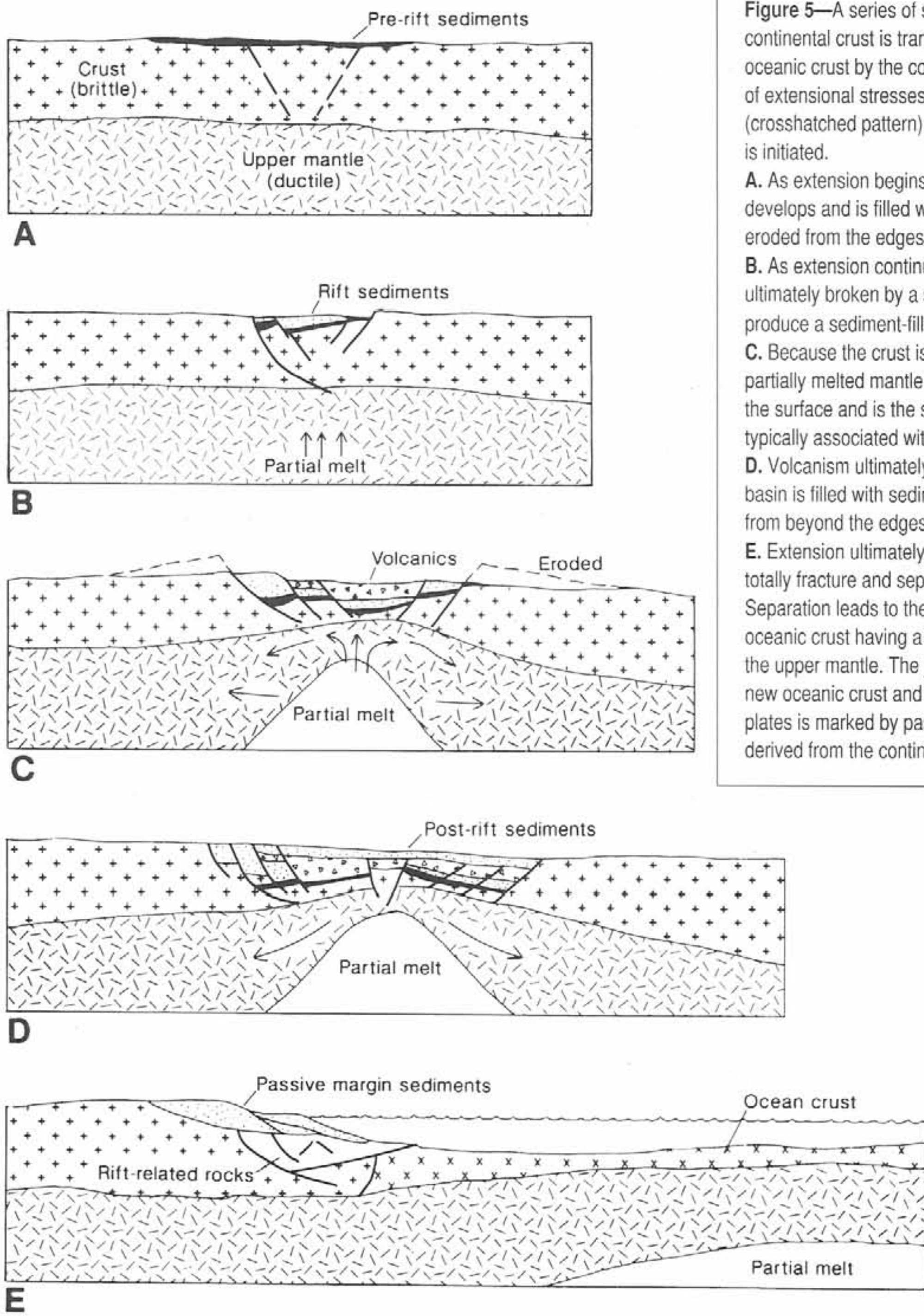


Figure 5—A series of sketches showing how continental crust is transformed into a new oceanic crust by the continued application of extensional stresses. Note that the crust (crosshatched pattern) is thinned as stretching is initiated.

A. As extension begins, a sag basin typically develops and is filled with sedimentary rocks eroded from the edges of the sag.

B. As extension continues, the crust is ultimately broken by a series of faults to produce a sediment-filled rift basin or graben.

C. Because the crust is considerably thinner, partially melted mantle material is brought to the surface and is the source of volcanic rocks typically associated with rifts.

D. Volcanism ultimately ceases and the rift basin is filled with sedimentary rocks derived from beyond the edges of the rift system.

E. Extension ultimately causes the crust to totally fracture and separate into two plates. Separation leads to the development of new oceanic crust having a composition like that of the upper mantle. The juncture between the new oceanic crust and the fractured continental plates is marked by passive margin deposits derived from the continent.

Figure 6—Relation between plate tectonics processes that tend to recycle rock material and sedimentary processes which tend to break down and redistribute fragments of broken rock.

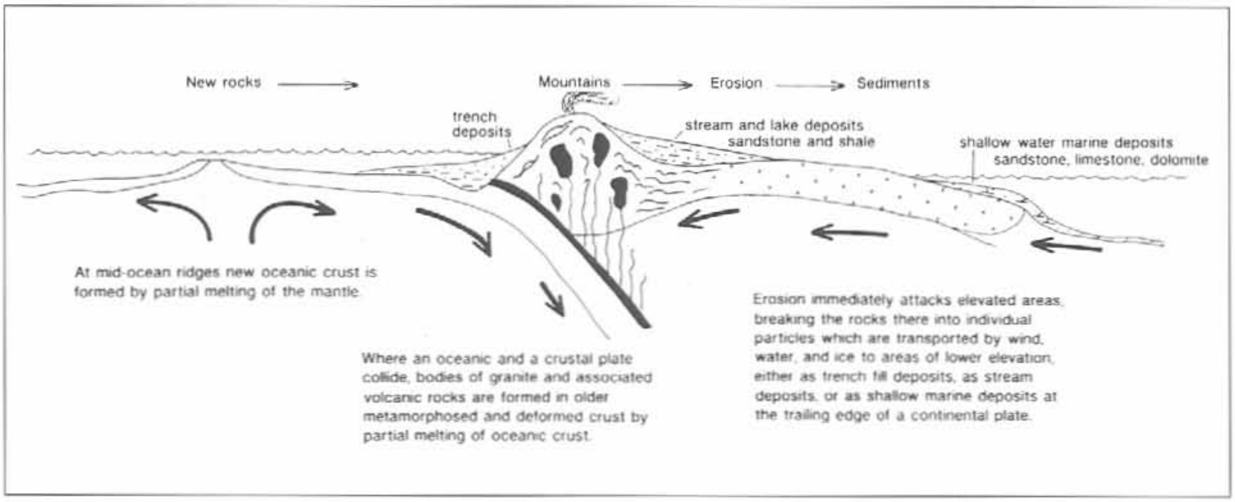


Plate tectonic processes and erosion are strongly linked. As shown in Figure 6, plate tectonic processes create new rocks and upland areas. Topographic differences between upland and lowland areas provide the potential energy needed for erosive processes to operate. Plate tectonic processes produce lowland areas that ultimately are filled with sedimentary materials eroded from the highlands.

It is one goal of geologists to understand the processes that create and destroy the rock record. It is another equally important goal to order those processes from oldest to youngest in order to understand how the earth has changed over time. In areas of flat-lying rocks, such as in southeastern Minnesota, it is easy to see that rocks at the bottom are older than those at the top of a sequence. Where fossils can be found you will also see that the rocks at the bottom have assemblages that are distinctly different from those at the top of the sequence. These differences in fossil assemblages or communities are extremely important in deciphering earth history. We can use them to equate the ages of rocks that may be thousands of miles apart.

Fossils, more importantly fossil assemblages, are used to divide geologic time into manageable segments. Fossils that had hard parts large enough to be visible to the human eye, first appeared in the rock record about 545 million years ago. This event is used by geologists to define the boundary between the Precambrian and the Phanerozoic (Figure 7). Phanerozoic means "distinct or visible animal life." Thus the Precambrian–Phanerozoic boundary at about 545 million years ago is one of the most important markers in geologic time. Figure 8 shows that the 80 percent of geologic time, associated with the Precambrian, contains only simple life forms. In contrast the remaining 20 percent, Phanerozoic time, contains a wide variety of plant and animal life.

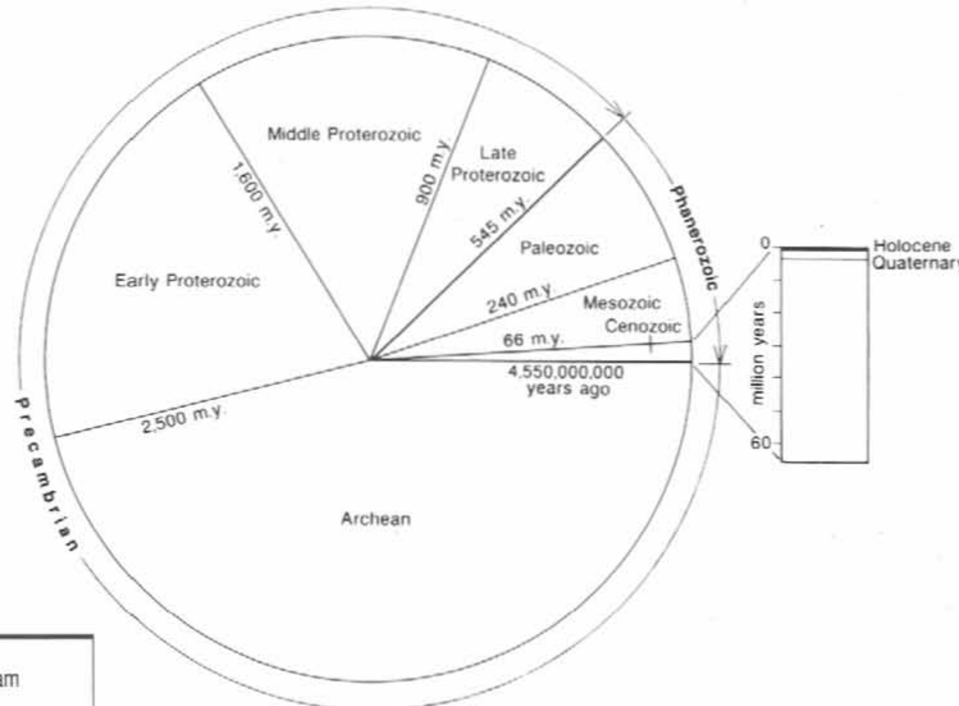


Figure 7—Pie diagram showing the relative proportions of various time units in earth history.

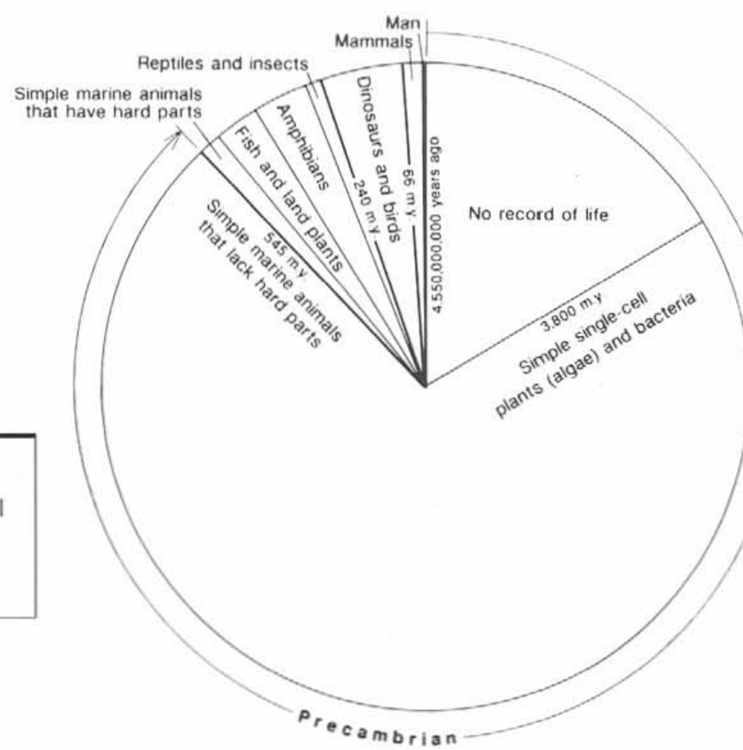


Figure 8—Pie diagram showing changes in the fossil record over geologic time.

On the basis of that plant and animal life, the Phanerozoic has been divided into three eras: the Paleozoic Era, the Mesozoic Era, and the Cenozoic Era (Figure 9). The eras in turn are divided into several periods, or smaller intervals of time called Cambrian, Ordovician, Silurian, Devonian, etc. Each interval is defined by its own unique fossil assemblages.

At the beginning of Paleozoic time animals lived in shallow seas; they were simple invertebrates such as trilobites, brachiopods, and crinoids—all animals without backbones. Consequently the early Paleozoic also is known as the "Age of Invertebrates." However, by about 500 million years ago—at the beginning of Devonian time, vertebrates or animals with backbones, such as fish, populated the seas, and plants grew on the land. By the end of Devonian time amphibians had evolved, and by the end of the Permian, air-breathing reptiles and insects were abundant. The Mesozoic Era is better known as the "Age of the Dinosaurs." These, and other reptiles, came in all sizes and dominated the Earth for 175 million years. They became extinct about 66 million years ago, long before early humans appeared on the Earth. During the Cenozoic Era, mammals such as horses, camels, and elephants became important, and finally humans appeared approximately 1.8 million years ago.

Evidence of life is contained in rocks that are as old as 3,800 million years in Greenland. However life in the Archean and Proterozoic consists mainly of very simple forms such as bacteria and blue-green algae until near the Precambrian–Phanerozoic boundary where more complex forms such as jellyfish first appear. Some of these organisms are still living today. Because these fossils have simple morphologies, they can not be used to subdivide the Precambrian part of geologic time. Other methods, therefore, have been devised to determine the age of rocks that lack fossils with hard parts. Figure 7 shows that the Precambrian is divided for convenience into two major intervals—Archean and Proterozoic—by a time boundary at 2,500 million years ago. The Proterozoic is further divided into three segments by time boundaries at 1,600 and 900 million years. Thus geologists say rocks which formed between about 4,550 million and 2,500 million years ago are Archean in age, whereas, those that formed between 2,500 million and 545 million years ago are Proterozoic in age. The ages of the rocks in question are determined by radioactive decay schemes measuring the minute amounts of certain naturally occurring radioactive elements they contain. Thus, geologic time is measured in two ways. Geochronometric or absolute time is based on radioactive decay, whereas, geochronologic or relative time is based on fossil evidence. Correlations between the two ways are constantly changing as new data occur, but presently held beliefs are summarized along the left side of Figure 9.

Age (millions of years ago)	Geologic Time Units			Rocks in Minnesota	Events in Minnesota	Characteristic Life
0–1.6	PHANEROZOIC	Cenozoic (recent life)	Quaternary	Peat, moraines, outwash, glacial lake sediments	Several intervals of continental glaciation	Age of Mammals
1.6–66	PHANEROZOIC	Cenozoic (recent life)	Tertiary	No record in Minnesota		Age of Mammals
66–138	PHANEROZOIC	Mesozoic (middle life)	Cretaceous	Chalk, dark shale, varicolored clay, sandstone, conglomerate	Sea enters Minnesota from the west	Age of Reptiles; Dinosaurs
138–205	PHANEROZOIC	Mesozoic (middle life)	Jurassic	Red-colored sandstone, shale, gypsum	Highland cut by west-flowing streams	Age of Reptiles
205–240	PHANEROZOIC	Mesozoic (middle life)	Triassic	No record in Minnesota		Age of Reptiles; Plesiosaurs
240–290	PHANEROZOIC	Paleozoic (ancient life)	Permian	No record in Minnesota		Vertebrates: Reptiles
290–330	PHANEROZOIC	Paleozoic (ancient life)	Pennsylvanian	No record in Minnesota		Vertebrates
330–360	PHANEROZOIC	Paleozoic (ancient life)	Mississippian	No record in Minnesota		Vertebrates: Amphibians
360–410	PHANEROZOIC	Paleozoic (ancient life)	Devonian	Limestone and dolomite	Sea enters Minnesota from the south	Vertebrates: Amphibians
410–435	PHANEROZOIC	Paleozoic (ancient life)	Silurian	No record in Minnesota		Fish
435–500	PHANEROZOIC	Paleozoic (ancient life)	Ordovician	Limestone, dolomite; some sandstone and shale	Seas cover Minnesota at intervals	Invertebrates: Corals, Cephalopods
500–545	PHANEROZOIC	Paleozoic (ancient life)	Cambrian	Sandstone, shale, glauconitic sandstone; some dolomite	Sea enters Minnesota from the south and west	Invertebrates: Trilobites; Animals with hard parts
545–4,550	Proterozoic and Archean		Precambrian	Lava flows, gabbro and sandstone; Iron-formation; Volcanic rocks, graywacke, granite	Midcontinent rift system; Penokean orogen; Greenstone belts	Animals without hard parts; First record of life

Figure 9—General stratigraphic column for Phanerozoic time emphasizing the geologic record in Minnesota.

A Brief Geologic History

In Minnesota, the bedrock—or the solid rock mass that lies at or below the land surface—is the record of a geologic history that extends from the middle part of Archean time to the later part of Cretaceous time. The rock record, however, is interrupted by large gaps of time called unconformities when apparently no rocks formed or when rocks that formed during an earlier time were later eroded.

Pre-Phanerozoic or Precambrian rocks underlie all of Minnesota and comprise part of what is called the North American Craton (Figure 1). Except on the north, adjacent to Canada, the Precambrian rocks are overlapped by sedimentary rocks of Phanerozoic age, which constitute a thin cover of relatively undisturbed rocks that thicken to the west, south, and east. That part of the craton where Precambrian rocks are exposed is called the Canadian Shield (Figure 1).

Although Precambrian rocks occur throughout much of Minnesota, they are covered by a mantle of Quaternary debris except in relatively few places. Consequently, to make a bedrock geologic map requires using techniques involving geologic mapping, drill core logging, and geophysical interpretation. An example of geophysical data used is illustrated in Figure 10. Combined geological and geophysical interpretations show that the Precambrian rocks can be divided into five broad subdivisions, or terranes. Of those, two are Archean, two are Early Proterozoic, and one is Middle Proterozoic in age.

In southeastern and northwestern Minnesota, the Precambrian rocks are overlain by sedimentary rocks that are early Paleozoic in age. In the western third of Minnesota, the Paleozoic and Precambrian rocks are partly covered by rocks of Mesozoic age (Figure 11). In the following descriptions of Archean, Early Proterozoic, Middle Proterozoic, and Phanerozoic rocks, reference should be made also to Figure 11.

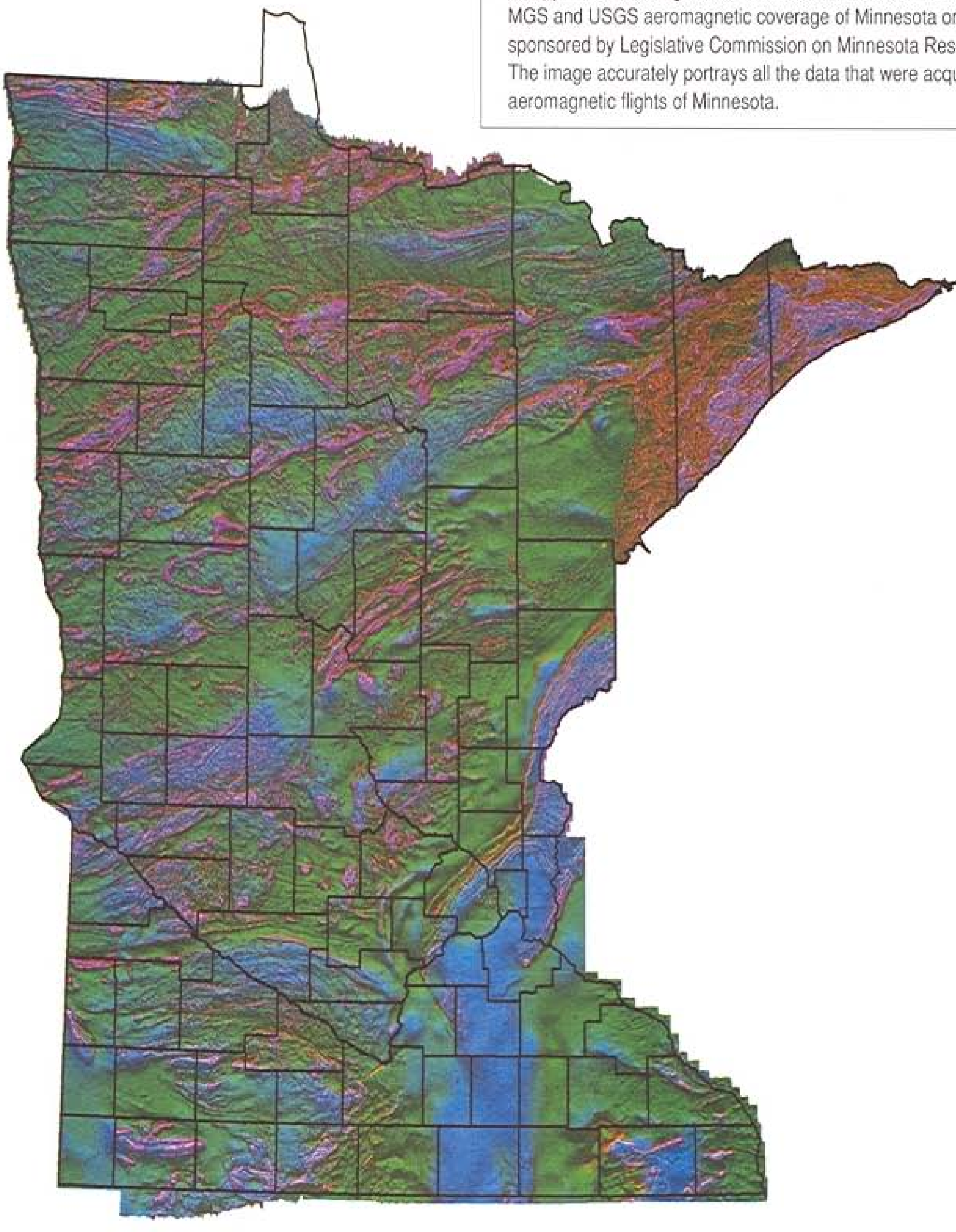
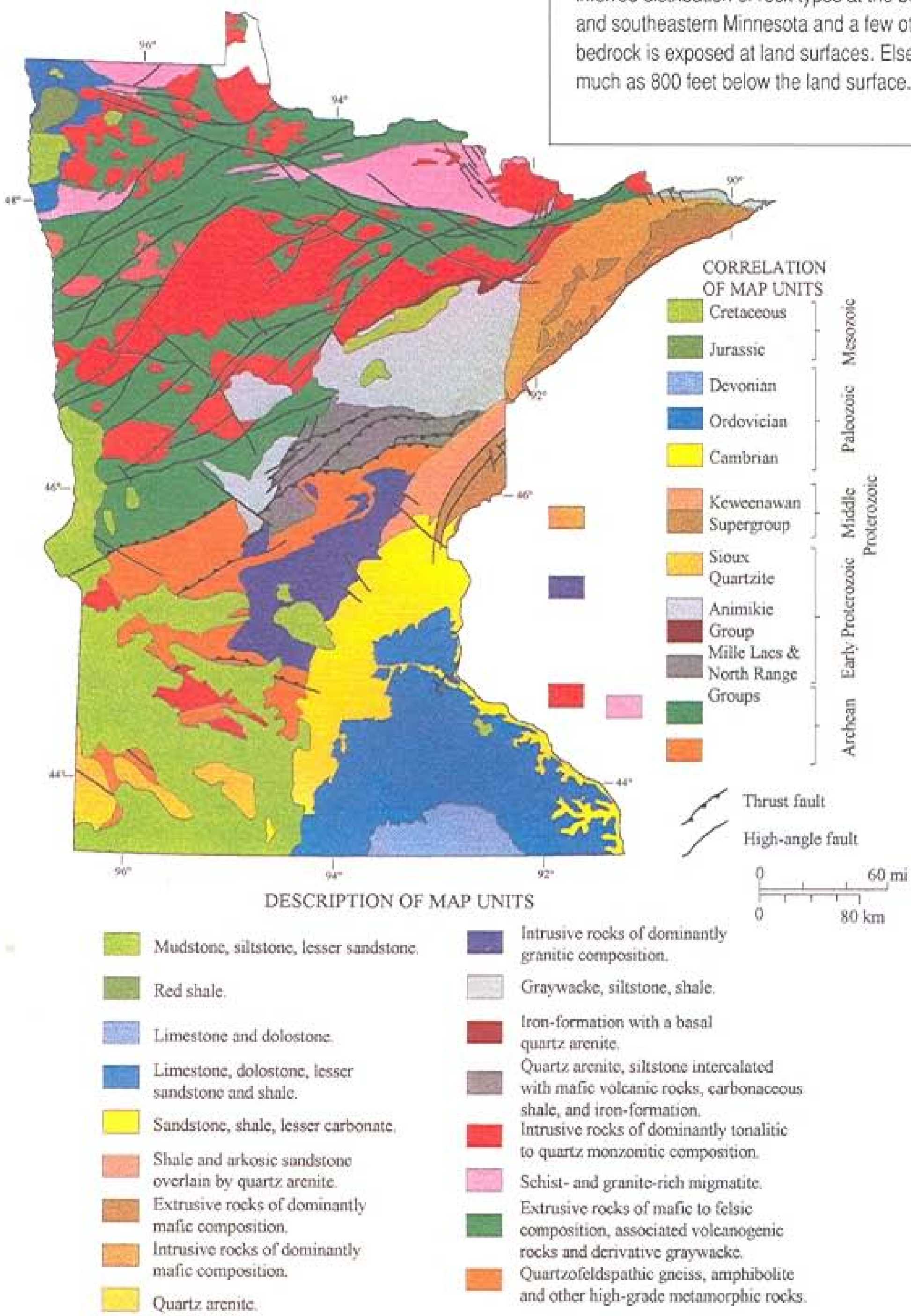


Figure 10—Magnetic properties of bedrock measured by airborne magnetic surveys. Broad green areas are regional magnetic lows, and broad blue areas are regional magnetic highs. Red, yellow, and white correspond to localized magnetic features such as magnetic iron formations, magnetite-bearing igneous intrusions, and pyrrhotite-bearing rocks. Source: Constructed from statewide MGS and USGS aeromagnetic coverage of Minnesota originally sponsored by Legislative Commission on Minnesota Resources. The image accurately portrays all the data that were acquired from aeromagnetic flights of Minnesota.

Figure 11—Bedrock geologic map of Minnesota. This map portrays the inferred distribution of rock types at the bedrock surface. In northeastern and southeastern Minnesota and a few other places (see Figure 21) the bedrock is exposed at land surfaces. Elsewhere the bedrock may be as much as 800 feet below the land surface.



Archean Rocks

Archean rocks include an older, middle to late Archean gneiss terrane in southwestern Minnesota and a much younger, late Archean greenstone-granite terrane in northern Minnesota. Both terranes contain large volumes of igneous and metamorphic rocks. The Archean gneiss terrane—colored orange on Figure 11—is best exposed along the Minnesota River Valley at Morton, Redwood Falls, Sacred Heart, and Ortonville. It also is exposed at a few places in Stearns, Mille Lacs, and Pine counties. The rocks are different kinds of gneiss—pronounced "nice"—a family of coarse-grained, banded metamorphic rocks. The origin of gneiss is not easily related to common experience. They formed miles below the surface of a craton between 3,600 and 3,000 million years ago. The gneisses were folded and faulted several times and intruded at depth by large volumes of granite and related igneous rocks—colored red on Figure 11—at 3,000 million years and again at 2,600 million years ago. Upper parts of the resulting craton were stripped away by erosional processes, ultimately exposing the once deeply buried rocks.

Components of the gneiss terrane are about 600 million years older than the Archean rocks in northern Minnesota. As such, the outcrops along the Minnesota River Valley contain the oldest rock in Minnesota as well as some of the oldest rocks in the Canadian Shield. Archean gneiss and granite are quarried for dimension stone at several localities along the Minnesota River Valley including the quarry at Morton where the world-famous "rainbow granite" is worked.

In northern Minnesota, younger Archean rocks are built of: (1) greenstone belts of relatively low metamorphic grade,—dark green on Figure 11—separated by large plutons of granite and other related coarse-grained igneous rocks;—red on Figure 11—and (2) metasedimentary belts which typically contain strongly deformed units of migmatite as well as a large proportion of granite—pink on Figure 11.

According to recent hypotheses that have been developed mainly in Canada, the greenstone belts are island arcs that represent assemblages of metavolcanic and related rocks. In contrast the metasedimentary belts are the remains of bodies of sediments formed between two island arcs or between an island arc and a craton. The greenstone and metasedimentary belts were merged by compressive tectonic processes similar to those occurring along the western margin of the Pacific Ocean today. Consequently, the several belts in Minnesota are typically bounded by regional strike-slip (shear) faults. Radiometric ages imply that individual greenstone belts formed between 2,700 and 2,750 million years but fused together to form a large craton at 2,670 to 2,710 million years ago.

The hypothetical evolution of a single greenstone belt is illustrated in Figure 12. It is based on the ideas that greenstone belts in northern Minnesota are similar to parts of subduction zone-related volcanic islands that now make up Indonesia or Japan in the western Pacific Ocean. As such, they are made up of basalt, a dark greenish gray, fine-grained igneous rock that formed from magma that flowed out onto a sea floor (Figure 12 A). During times when volcanic activity was minimal, silica and iron-rich minerals such as hematite (an iron oxide), siderite (an iron carbonate), or pyrite (an iron sulfide) accumulated on the sea floor to form bodies of what we call "iron-formation" (Figure 12 A). In places on the sea floor volcanic centers composed mainly of dacite, a white to light gray volcanic rock, formed by explosive volcanic

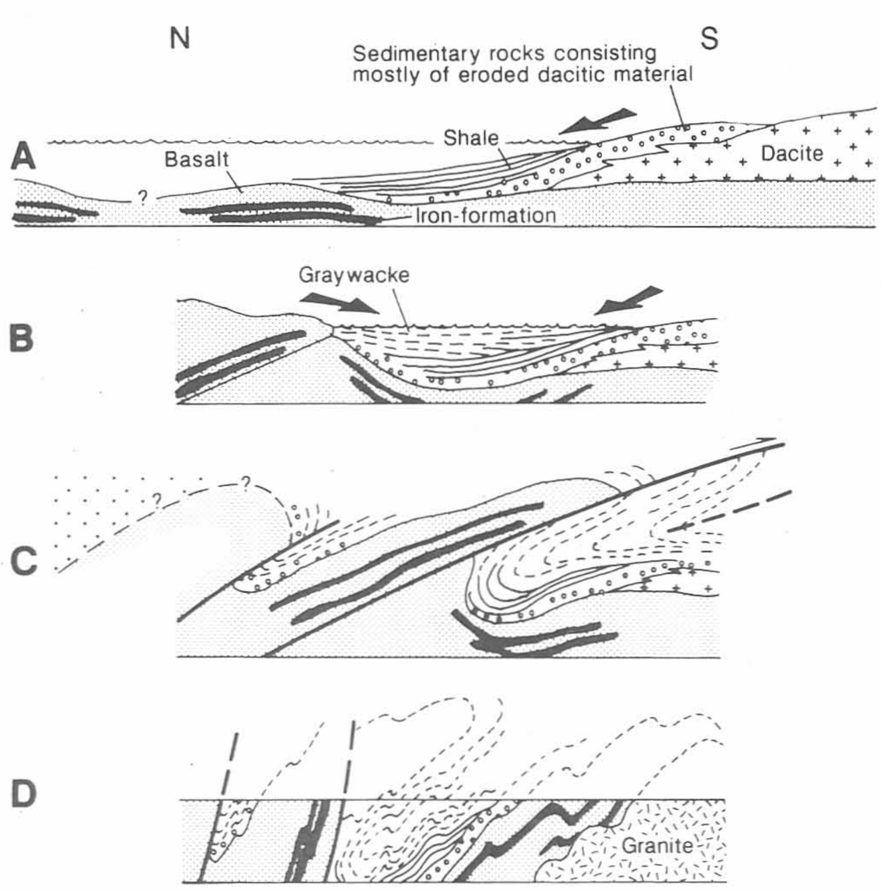


Figure 12—Schematic depiction showing the evolution of an Archean greenstone belt in northern Minnesota.
A. Deposition started with the accumulation of basalt and iron-formation generally below sea level. A felsic volcanic center consisting mostly of dacite accumulated to a height above the wave base. Erosion supplied felsic volcanic detritus (rock fragments) to a depositional basin formed on top of the mafic rocks.
B. Southward-directed compression produces a depositional basin bordered on the north by upthrust blocks of basalt that contributed detritus to the depositional basin forming graywacke.
C. Compression continues and sedimentation ceases as uplifted blocks of basalt were thrust over sedimentary deposits.
D. The last event in the evolution of this greenstone belt involves the emplacement of large granite batholiths and folding of all the rocks about vertical fold axes.

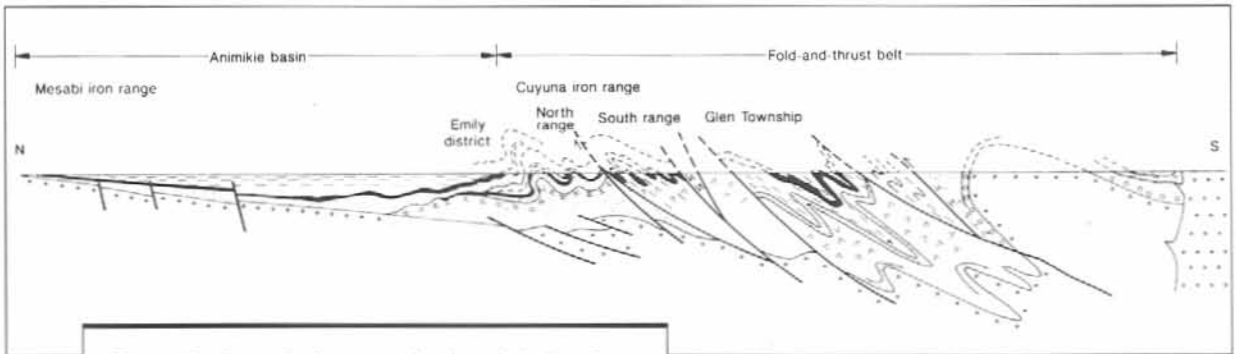


Figure 13—Generalized cross section through the Penokean orogen showing how it can be divided into an older fold-and-thrust belt to the south and a younger foredeep basin to the north.

processes. Dacitic volcanism typically lead to islands that grew to near sea level where they could be subjected to erosive processes. Sandstone, consisting mostly of eroded dacite fragments and interbedded shale were deposited as fringes surrounding the volcanic centers (Figure 12 A). Volcanism and associated sedimentation were interrupted by compressional tectonic processes involving the uplift of previously formed rocks along thrust faults to positions well above sea level. As a consequence, well-defined basins formed and received thick accumulations of detritus from both basaltic and dacitic sources (Figure 12 B). Continued compression and thrust faulting terminated sedimentation and in many cases re-folded already complexly folded sedimentary accumulations into large overturned folds (Figure 12 C). Toward the end of Archean time the folded and faulted rocks were intruded by large batholiths of granite that shouldered aside the rocks by refolding them about near-vertical axes (Figure 12 D). Subsequent erosion removed much of the folded material to expose alternating belts of granite and greenstone.

Rocks of the greenstone belts are particularly well exposed in the western part of the Boundary Waters Canoe Area and in the Vermilion Iron Range between Tower-Soudan and Ely. The latter contains impressive exposures of iron-formation, especially at Soudan Underground Mine State Park.

Early Proterozoic Rocks

Early Proterozoic rocks in east-central and northern Minnesota form part of what is called the Penokean orogen, a mountain-building event that culminated around 1.85 billion years ago. These rocks are part of a much larger feature that extended from the central part of South Dakota to Lake Huron and perhaps farther to the east. The eroded remnants of the Penokean orogen have geologic similarities to the roots of 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.

The Penokean orogen can be divided into two distinct belts of different age and geologic history (Figure 13). An older fold-and-thrust belt defines the southern side of the orogen, whereas the foredeep basin, called the Animikie basin defines the northern half of the orogen. The fold-and-thrust belt—colored dark grey on Figure 11—is poorly exposed in the general vicinity of Denham to Moose Lake in Carlton County southwest of Duluth and includes the Cuyuna Iron Range. It consists of a variety of metasedimentary rocks that were deposited through time successively as extensional processes stretched the Archean basement rocks through sag and rift stages to ultimately produce a passive margin. New oceanic crust, including an island arc formed well to the south in what is now Iowa. Sedimentary rocks, including

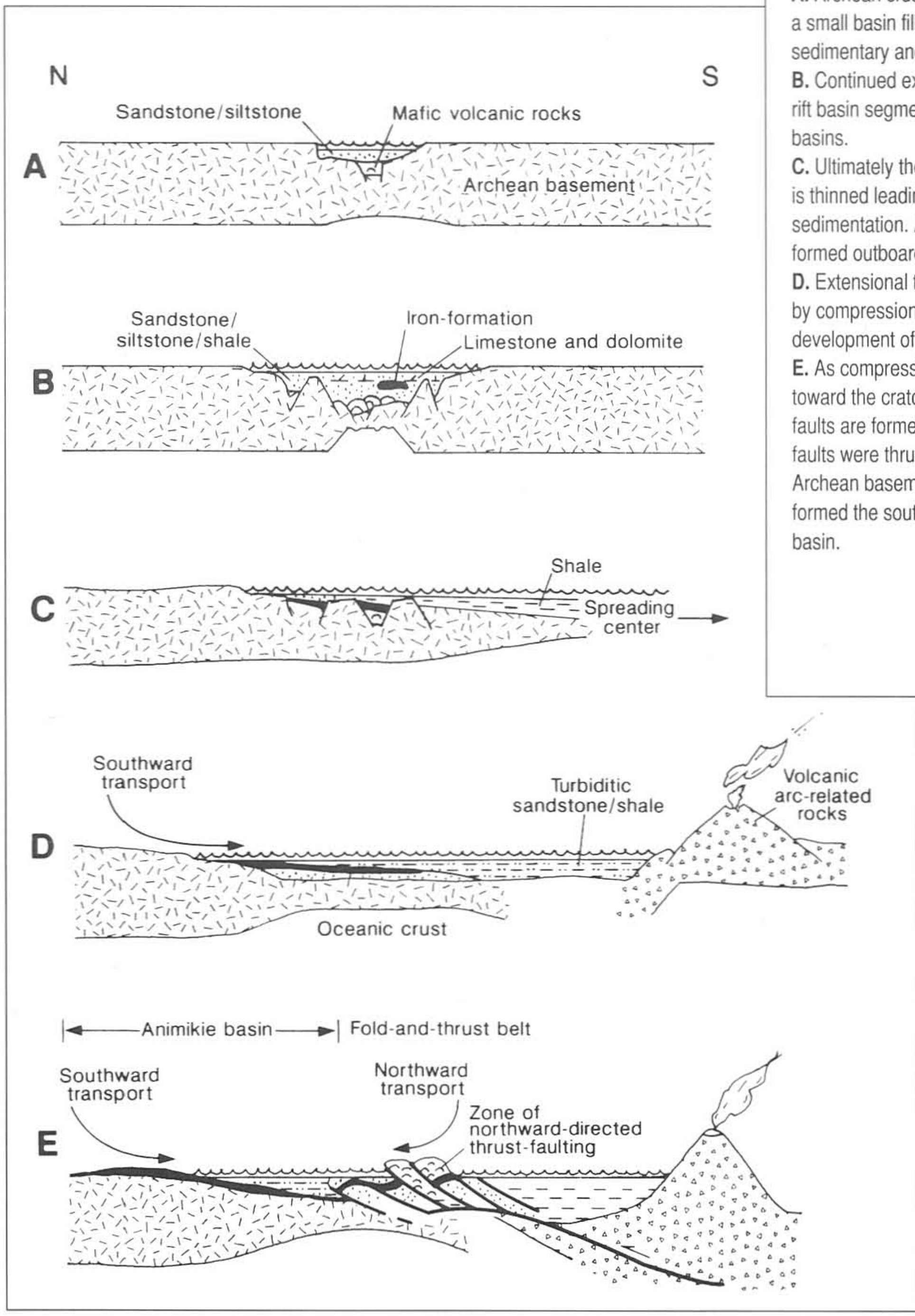


Figure 14 A–E—Schematic depiction of the evolution of Early Proterozoic rocks in the Penokean orogen.

A. Archean crust is extended to produce a small basin filled with various kinds of sedimentary and volcanic rocks.

B. Continued extension leads to an enlarged rift basin segmented in places into smaller basins.

C. Ultimately the Archean basement is thinned leading to passive margin sedimentation. At this time new oceanic crust formed outboard of the passive margin.

D. Extensional tectonic forces are replaced by compressional tectonic forces, causing the development of a volcanic arc to the south.

E. As compression continues, the arc moves toward the cratons and south-dipping thrust faults are formed. The upper plates of these faults were thrust to the north over the Archean basement. This fold-and-thrust belt formed the southern margin of the Animikie basin.

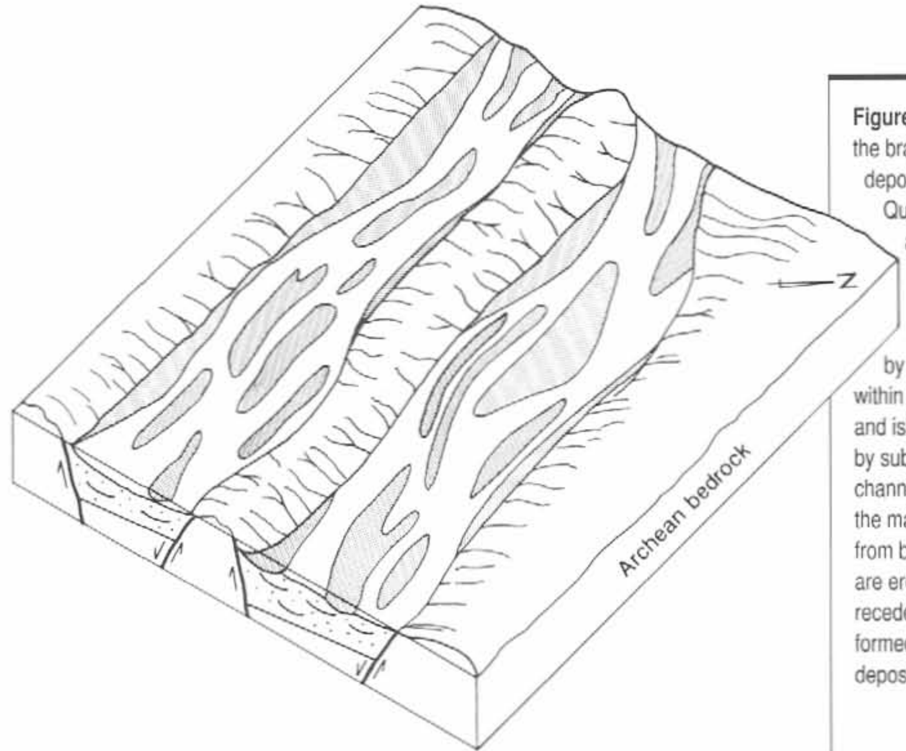


Figure 15—Sketch showing the braided stream system that deposited sediments of the Sioux Quartzite. The stream systems are contained in two fault-bounded valleys or graben oriented in a northwesterly direction and separated by a horst. The shaded areas within the main channels are bars and islands that are separated by sub-channels within the main channels. At times of high water, the main channels are flooded from bank to bank and the islands are eroded away. As the water receded, new bars and islands formed and are covered with thin deposits of clay.

iron-formation, were derived from northern sources (Figure 14 A, B, C). Ultimately the tectonic regime changed from that of extension to that of compression. As the newly formed ocean closed upon itself and the volcanic arc moved toward the craton (Figure 14 D), the passive margin deposits were folded and faulted up and over the older Archean basement on large thrust faults (Figure 14 E). The up-faulted rocks formed a highland that bordered a sedimentary basin—called a foredeep—located to the north. Sediments in this basin were derived from both northern and southern sources. This became the repository for a younger group of rock—colored light gray on Figure 11—now exposed along the Mesabi Iron Range in northern Minnesota and near Cloquet and Thomson in Carlton County southwest of Duluth. The Carlton County exposures include mostly graywacke and shale, but iron-formation and underlying quartzite—collectively colored red-brown on Figure 11—are exposed on the Mesabi Iron Range.

In addition to being complexly deformed and metamorphosed, the older fold-and-thrust belt is permeated by large bodies of granite—colored purple on Figure 11—emplaced between 1,820 and 1,770 million years ago. In contrast, the foredeep deposits are relatively undisturbed except for regional tilting and local faulting.

In southwestern Minnesota, the Sioux Quartzite—colored dark yellow on Figure 11—forms a second Early Proterozoic terrane. It consists mostly of a quartz arenite that accumulated as sand-size material that was carried by rivers flowing through a series of small, northwest-trending, fault-bordered rift basins set into Archean rocks. Two such basins separated by a small horst are illustrated in Figure 15. A well-defined erosional surface involving millions of years of erosion separates the Archean rocks from the Sioux Quartzite. Later, metamorphism recrystallized the sandstone into the hard quartzite seen today in the bluffs of Blue Mounds State Park. Thin beds of reddish-brown mudstone (catlinite or pipestone) in the quartzite at Pipestone National Monument are still being quarried and carved today, following a custom that started as early as A.D. 900–1200.

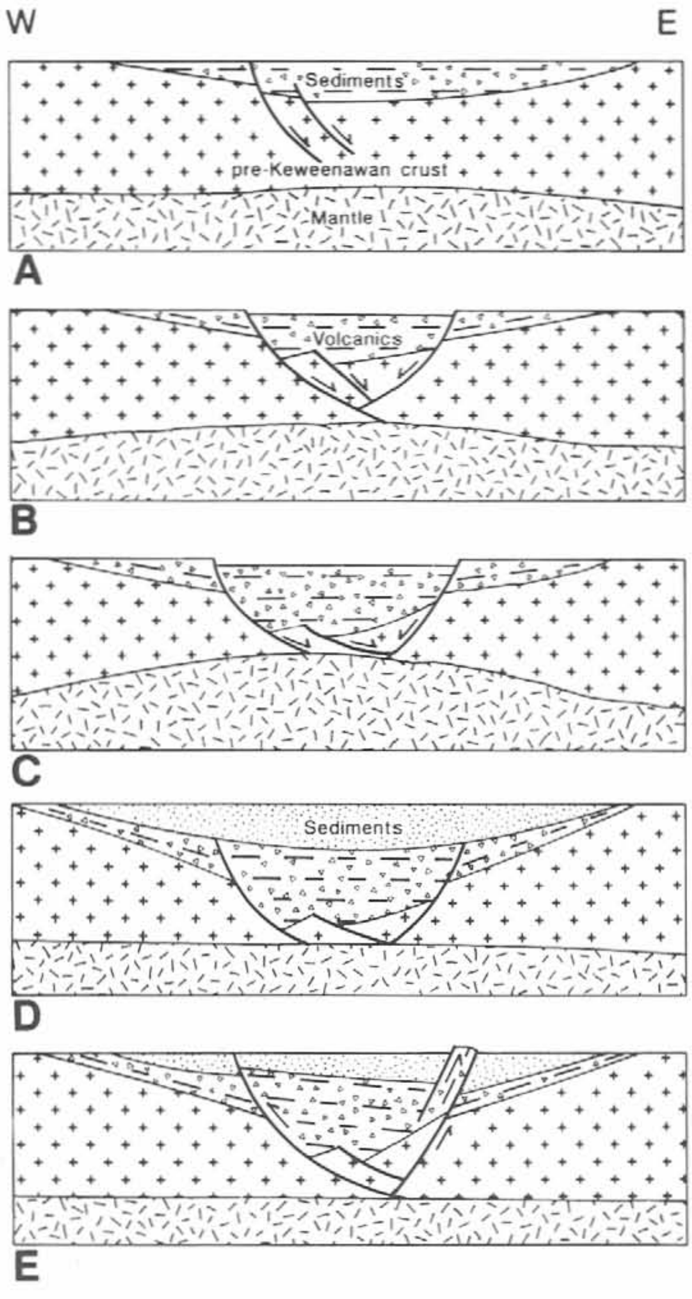


Figure 16—Schematic depiction for development of the Midcontinent Rift System in the general vicinity of the Twin Cities.

A. Rifting begins with the development of a broad sag basin bounded on one side by normal faults.

B. As the crust continues to thin, a rift basin evolves and grows in size. Hot mantle material works to fill the fault-bounded basin with extrusive volcanic rocks.

C. Ultimately extension and volcanism cease. The central part of the rift basin and flanking rocks collapse.

D. The resulting depression is filled with sedimentary rocks derived from outside the rift system.

E. Sedimentation in the rift system terminates when original graben-bounding normal faults were transposed to high-angle reverse faults. Rocks of the central graben are thrust up to produce a central horst of volcanic rocks flanked by half-grabens filled with sedimentary rocks.

Early Proterozoic rocks are an important source of economic materials. Large mines on the Mesabi Iron Range in the area of Hibbing, Virginia, and Hoyt Lakes are a major source of iron ore, from which taconite pellets are made for the manufacturing of steel. The Cuyuna Iron Range in east-central Minnesota contains major quantities of manganese that have not yet been developed. Several quarries developed in Early Proterozoic granite are in operation near St. Cloud. These quarries provide dimension stone used around the world, as well as crushed rock aggregate for road and railroad construction. The Sioux Quartzite also is quarried for aggregate.

Middle Proterozoic Rocks

Middle Proterozoic rocks in Minnesota are associated with the Midcontinent Rift System, a feature that extends from the east end of Lake Superior to Duluth, then to the south along the Minnesota–Wisconsin border to Iowa, and on into Kansas. Much of the rift system is covered by younger Phanerozoic rocks and can be detected only by geophysical methods. The history of the rift started as a depression or sag basin that formed around 1,100 million years ago by thinning of the lithosphere (Figure 16 A). As the lithosphere continued to thin, a basin formed, and fractures allowed magma to work its way to the surface as lava flows—colored dark brown on Figure 11. Volcanism and subsidence in the basin were more or less contemporaneous processes resulting in very thick accumulations of lava. When volcanism ceased, sequences of sand-size material—now sandstone—colored peach on Figure 11—were deposited by streams flowing across the tops of lava flows. The lava flows are well exposed along Lake Superior, and their well-preserved flow features are much the same as those in modern-day volcanic rocks such as those found in Hawaii. The Lake Superior agate, for which Minnesota is famous, originally formed as fillings in the vesicles of these volcanic basalts.

The base of the volcanic sequence was intruded by several kinds of igneous rocks including gabbro (consisting of pyroxene and plagioclase), troctolite (consisting of olivine and plagioclase), and anorthosite (consisting almost entirely of plagioclase). Some of these rocks may have crystallized in storage chambers that fed the lava flows which were extruded higher up in the crust. These intrusions form a large body of rock in northern Minnesota called the Duluth Complex—colored light brown on Figure 11. It is interesting to note that anorthosite is a major part of the highland areas on the moon. Anorthosite from the Duluth Complex has been used in laboratory experiments as a substitute for samples of the "real thing" brought back (expensively) from the moon.

No rocks of Late Proterozoic age have been found in Minnesota. Either they were never deposited or were removed by erosion before the beginning of Phanerozoic time.

Rocks similar to the lava flows along the North Shore are mined extensively for copper in Michigan. In Minnesota, a large resource of copper, nickel, and associated platinum group elements, gold and titanium, exists at the base of the Duluth Complex especially south of the area from Babbitt and Ely.

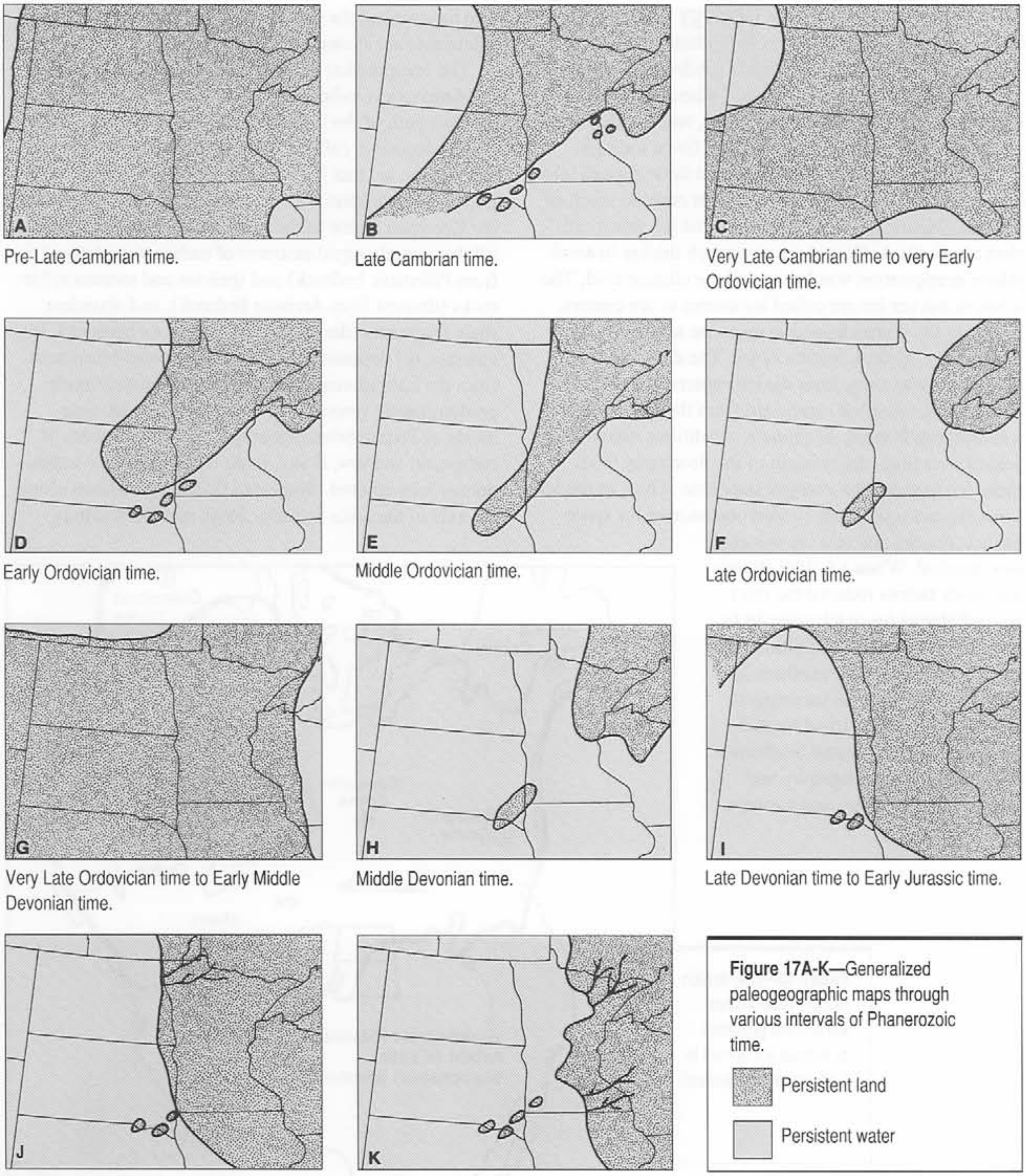
Phanerozoic Rocks

The Phanerozoic spans the next eon of earth history. During that 545 million years of geologic time, Minnesota was part of a stable continent that was inundated by several advances, called "transgressions," and retreats, called "regressions," of the oceans. Those advances and retreats are illustrated in Figure 17. During Cambrian time, a continent of weathered rock (Figure 17 A) was gradually covered by shallow seas from the northwest and the southeast (Figure 17 B). This transgression phase continued through Late Cambrian time. Quartz-rich sandstone interlayered with thin beds of shale were deposited in near shore areas, while chemically precipitated limestone and dolomite were also deposited in offshore areas. The sea withdrew or regressed at the end of Cambrian time (Figure 17 C), but again readvanced in Early Ordovician time. During that readvance (Figure 17 D–F), the sea transgressed over more and more land so that by Late Ordovician time the sea ultimately covered much of Minnesota including a northeast-trending landmass called the Transcontinental Arch. The arch was fringed by shaly deposits, but as it was submerged, the clastic rocks were replaced by limestone and dolomite. The sea withdrew from Minnesota mainly to the west toward the end of Late Ordovician time (Figure 17 G). Consequently, much of Minnesota was exposed to erosive processes that removed considerable amounts of these earlier deposited sediments. The sea readvanced during Middle Devonian time, depositing dominantly shallow-water limestone and dolomitic limestone, (Figure 17 H). The sea retreated again, this time to the west of Minnesota during the interval between Middle Devonian and Middle Jurassic times (Figure 17 I). During Late Jurassic time, a sea again readvanced to the east, but the only Jurassic rocks in Minnesota are stream deposits along the boundary with North Dakota (Figure 17 J). During that time, Minnesota was subjected to intense tropical weathering, an event that extended well into Cretaceous time. Thick layers of kaolin clay were developed that are very much like laterite and bauxite deposits formed in modern tropical regions. The sea continued to advance from the west to the east and in Late Cretaceous times coastal and shallow marine sediments were deposited over much of western Minnesota (Figure 17 K). Channels of west-flowing streams were filled with mixtures of shale, organic-rich clay, and lignite. As the sea continued to progress from the west to the east, the stream deposits were progressively covered by younger deposits of marine sandstone, siltstone, and shale.

Much of Minnesota was once covered by Cretaceous rocks, but significant quantities were eroded prior to Quaternary time. Consequently, the Cretaceous rocks now occur as an erosionally dissected patchy blanket in southwestern Minnesota, and as small outliers or remnants in other parts of the state. An outlier of Cretaceous rock at the Hill Annex Mine, on the Mesabi Iron Range in northern Minnesota, is noted for its fossils including the shells of squid-like ammonites and shark teeth.

In general, the erosional processes that removed Cretaceous strata also removed variable amounts of the pre-Cretaceous basement. Much of the erosion occurred prior to the onset of glaciation in Quaternary time. The resulting distribution of eroded preglacial highlands and lowlands had a profound effect on the distribution of various ice lobes that covered Minnesota in Pleistocene time.

Figure 17A-K



A. Pre-Late Cambrian time.

B. Late Cambrian time.

C. Very Late Cambrian time to very Early Ordovician time.

D. Early Ordovician time.

E. Middle Ordovician time.

F. Late Ordovician time.

G. Very Late Ordovician time to Early Middle Devonian time.

H. Middle Devonian time.

I. Late Devonian time to Early Jurassic time.

J. Middle Jurassic time.

K. Late Cretaceous time.

Figure 17A-K—Generalized paleogeographic maps through various intervals of Phanerozoic time.

Quaternary Geology

The term Quaternary refers to the last 5 million years of geologic time. Geologists subdivide it into the Pleistocene or the "Great Ice Age," when nearly all of Minnesota was covered by glacial ice, and the Holocene or Recent, a time since the end of the Great Ice Age.

In Pleistocene time, glacial ice that flowed south into Minnesota came from an ice sheet that covered much of Canada (Figure 18). In some places that ice was more than a mile thick. Glacial ice was much thicker in areas where precipitation was heavy and the climate cold. The areas of thicker ice are called ice domes or ice centers.

Ice in the domes flowed in response to the pressure and gravity on thick masses of ice. The direction or movement was away from the ice centers. Ice streams or ice lobes advanced southward from the Keewatin and Labradorean Domes. As climatic conditions waxed and waned over time, the strength of the flow away from those ice centers also changed over time. Thus, as the ice lobes flowed south, they battled one another for space as their masses and relative velocities changed. When a milder climate and other factors reduced the thickness of glacial ice, a lobe ceased to flow and it stagnated and ultimately melted back to a more northern location. Places where the ice stopped and stagnated are marked by end moraines or complicated landforms having a rugged topography and numerous small lakes and swamps. The locations of the more prominent end moraines in Minnesota are shown on Figure 19.

The composition of the glacial sediments deposited in Minnesota is indicative of the type of bed material in the flow path of the ice lobes. The most common kind of glacial deposit is called till—material deposited by and beneath the ice that is generally a mixture of clay, sand, gravel, and boulders. Lobes that entered Minnesota from the Keewatin Dome to the north and northwest deposited till that contain equal amounts of carbonates (derived from Paleozoic bedrock) and igneous and metamorphic rocks (derived from Archean bedrock), and abundant shale fragments (derived from Cretaceous bedrock). In contrast, till deposited by lobes that entered Minnesota from the Labradorean Dome to the northeast contain predominantly igneous and metamorphic rock fragments of Precambrian parentage, variable amounts of carbonate, and few, if any, shale fragments. One Labradorean lobe entered Minnesota from the northeast along the axis of the Lake Superior basin and the resulting

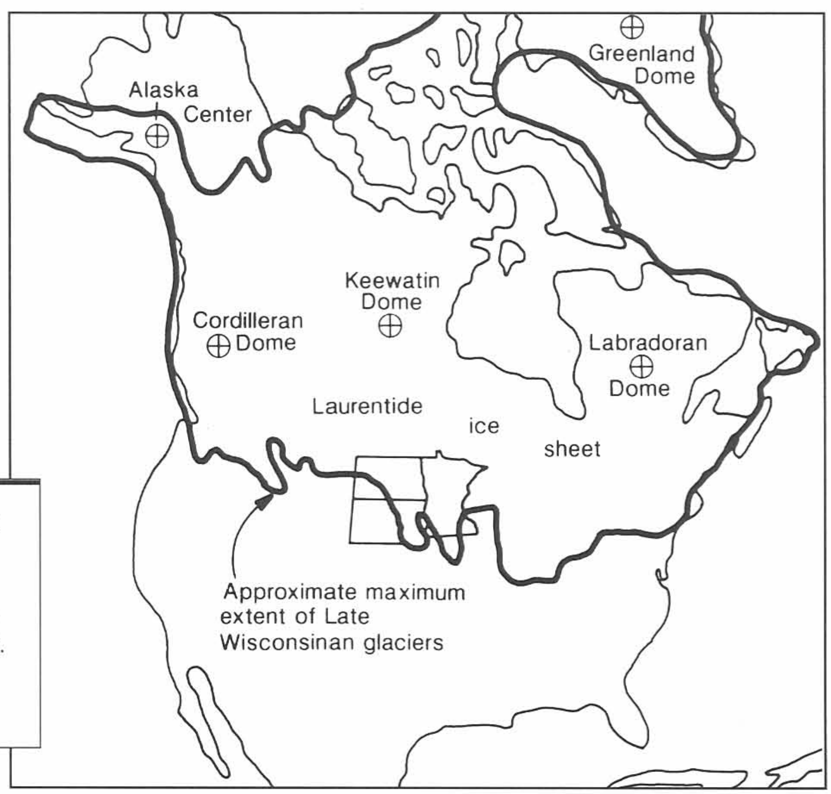


Figure 18—Distribution of Late Wisconsinan ice and the positions of various ice domes in Canada and Greenland.

till is marked by fragments of basalt and red sandstone derived from bedrock in the Midcontinent Rift System.

In parts of the state, as in north-central Minnesota, glacial deposits are more than 650 feet thick, and record as many as 13 separate ice lobes, alternating from northwestern, northeastern, and east-northeastern sources. The history of these deposits is poorly understood. As expected, deposits exposed at the surface are much better understood. They were laid down by numerous ice advances toward the end of Pleistocene time during what geologists call the Late Wisconsinan (25,000 to 10,000 years ago). The maps in Figure 20 show the surface distribution of glacial deposits derived from several northwestern and northeastern advances and the locations of their more important end moraines. It also shows that glacial materials older than the Late Wisconsinan are found at the surface only in the southeastern and southwestern corners of the state.

A second major type of glacial-related sediment that consists of material that was deposited by running water is also shown as a separate map unit in Figure 21. This sediment consists mainly of sand and gravel that was washed out of a melting glacier and thus is referred to as "outwash"—colored purple on Figure 21. As shown in Figure 22, outwash deposits form at the front of glaciers by meltwater streams flowing under and off the ice. Outwash deposits are important sources of groundwater. A third type of glacial sediment also shown as a separate map unit—colored light green on Figure 21—was deposited on the floors of lakes to produce smooth topographic features known as glacial lake plains. Such plains can range in size from a few acres to many hundreds of square miles. They generally formed in places where glacial ice blocked the routes of major drainage ways, damming the water in large natural reservoirs (Figure 22). In Minnesota, the largest of these glacial lakes—Glacial Lake Agassiz—inundated more than 350,000 square miles in northwestern Minnesota and adjoining parts of North Dakota and Canada, although at no single time did water cover the entire area.

Toward the end of Pleistocene time, a change to an increasingly continental climate—marked by warmer summers and colder winters—caused ice sheets to shrink. Consequently, they became much thinner and their margins melted rapidly. That period of melt back marks the Pleistocene–Holocene boundary which is placed at 10,000 years before present.

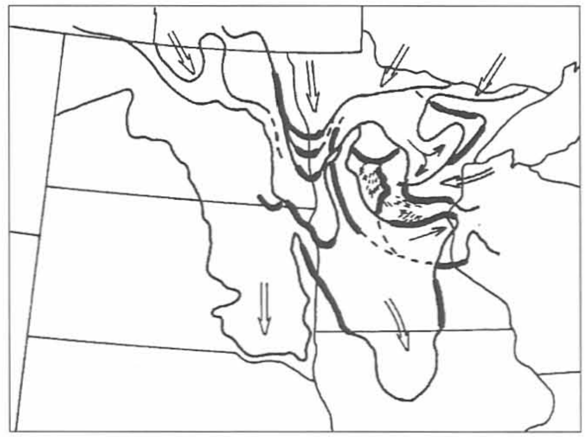
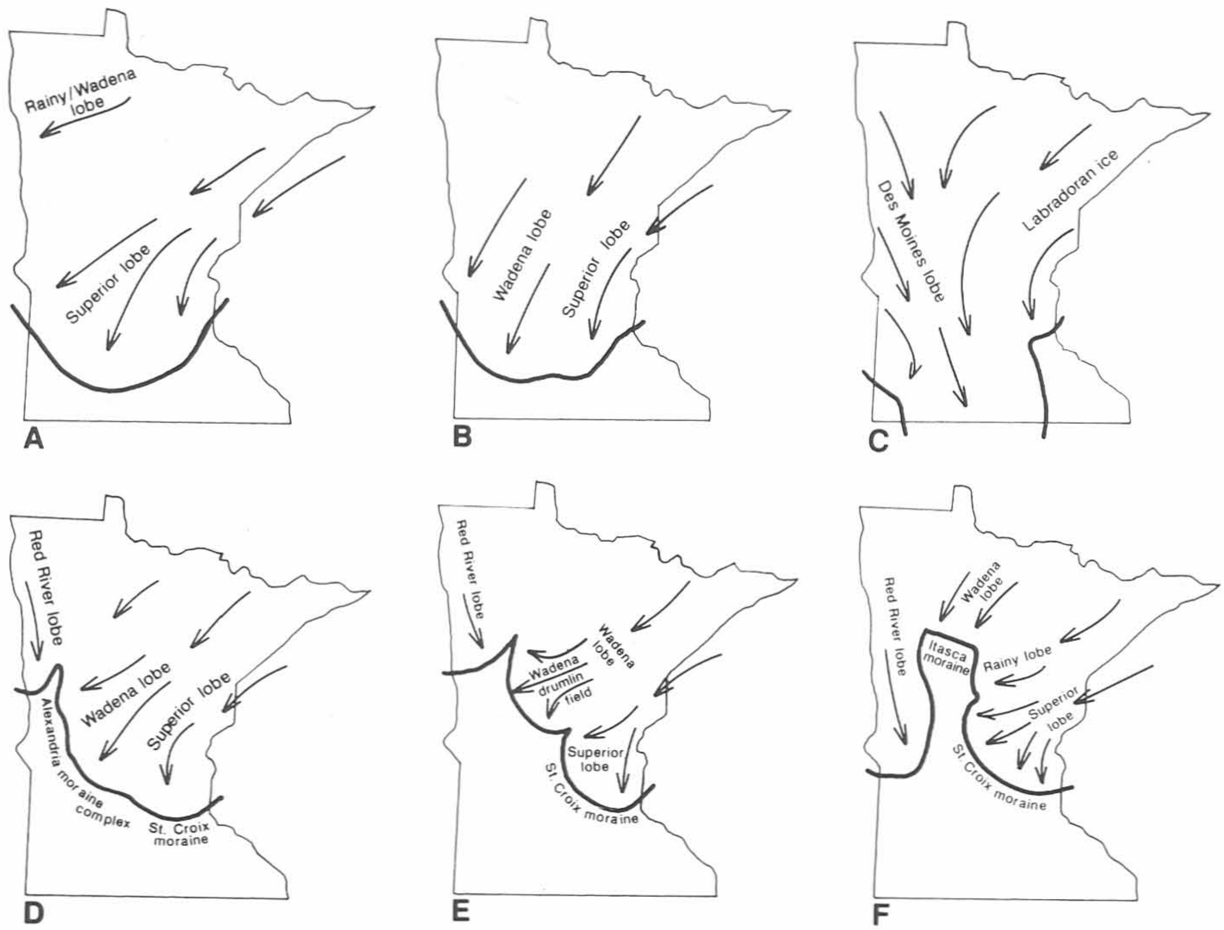


Figure 19—A sketch map showing the locations of some of the ice lobes that crossed Minnesota and their associated end moraines (heavy black lines). Note that all of the ice lobes shown were not present in Minnesota at the same time as evident by overlapping moraines.

A unique feature of the Holocene in Minnesota is the development of large peat bogs—colored light orange on Figure 21. Peat is partially decomposed and disintegrated vegetable matter that has undergone some physical and chemical changes. The largest peat area in the state is the lake plain associated with Glacial Lake Agassiz. However, most of the peat does not occupy depressions, but rather occurs as built up deposits on the poorly drained land. Peat deposits of similar origin occur on lake plains associated with Glacial Lake Upham in St. Louis County and Glacial Lake Aitkin in Aitkin County. The peat is a potentially valuable deposit in Minnesota although it is not widely used at the present time.

Sand and gravel, typically extracted from glacial outwash deposits, are used for aggregate in the construction industry for houses, bridges, and roads. Figure 23 and the attached fact sheet summarize the mineral industries in Minnesota.

Figure 20 A–H



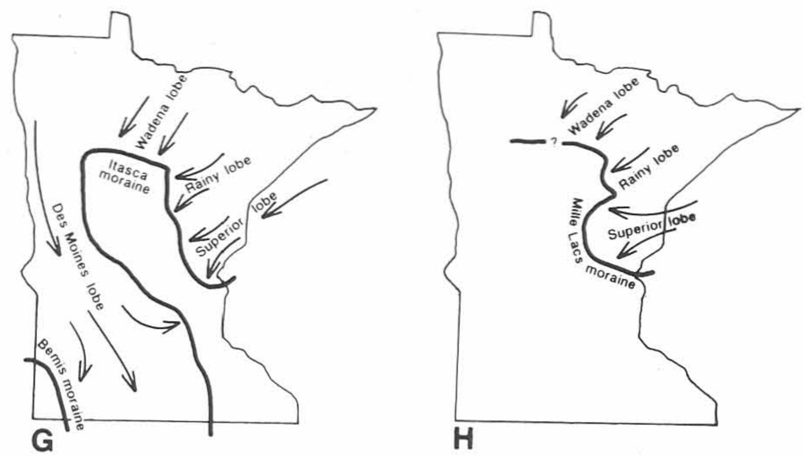


Figure 20—Summary diagram showing the several ice advances and their associated end moraines that affected Minnesota in Late Wisconsinan time. Ice advances are arranged from oldest (A) to youngest (H). It is assumed that each advance is separated from the next advance by a period when the ice retreated to a position beyond the state boundaries.

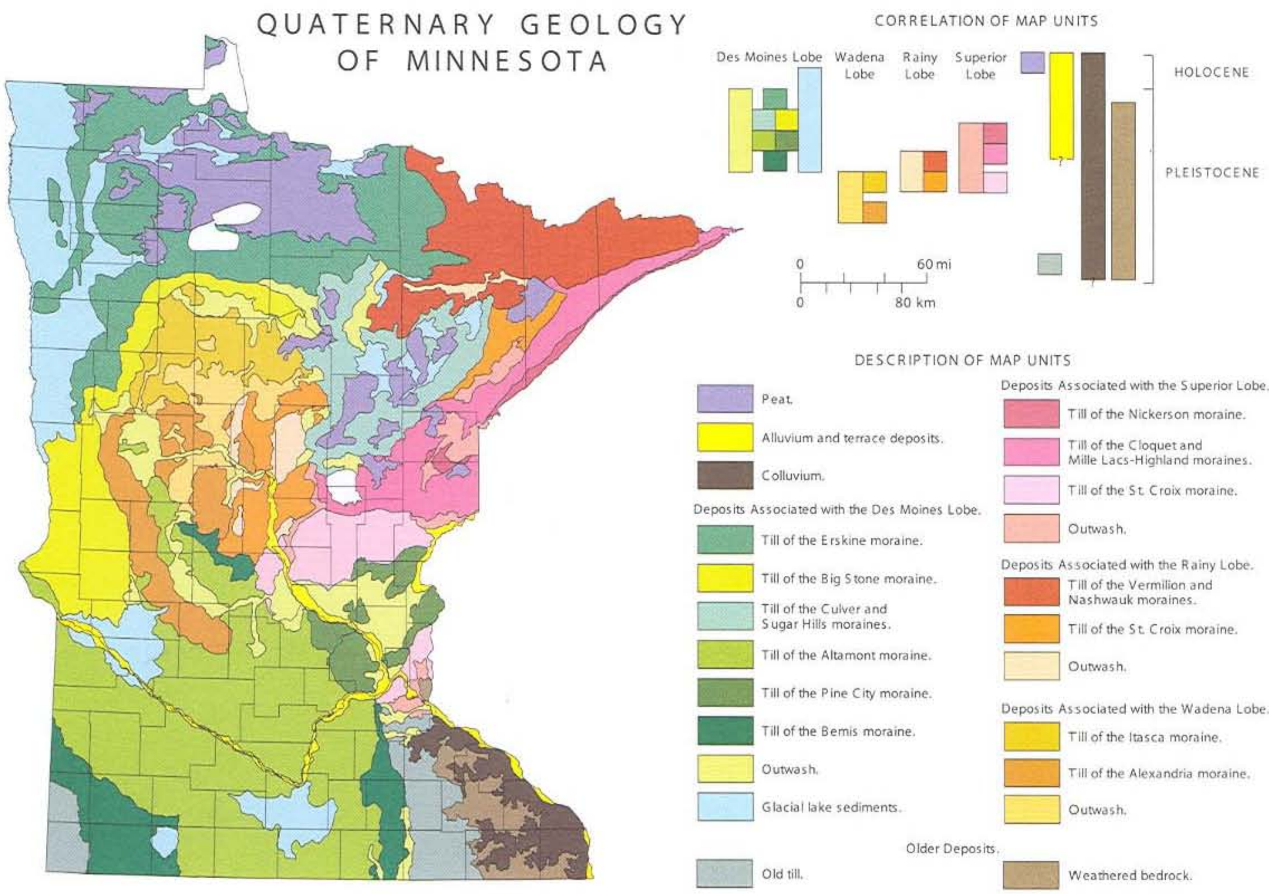


Figure 21—This simplified geologic map shows the general distribution of surficial sediments in Minnesota. During the Pleistocene Epoch (2 million-10,000 years ago), glaciers advanced into Minnesota several times from different directions-the most recent include: the Superior lobe from the northeast; the Rainy lobe from the north-northeast; the Wadena lobe from the north; and the Des Moines lobe from the northwest. This map is modified from Hobbs, H.C., and Goebel, J.E., 1982, Geologic map of Minnesota, Quaternary Geology: MGS State Map Series S-1, 1:500,000. Digital compilation by B.A. Lusardi.

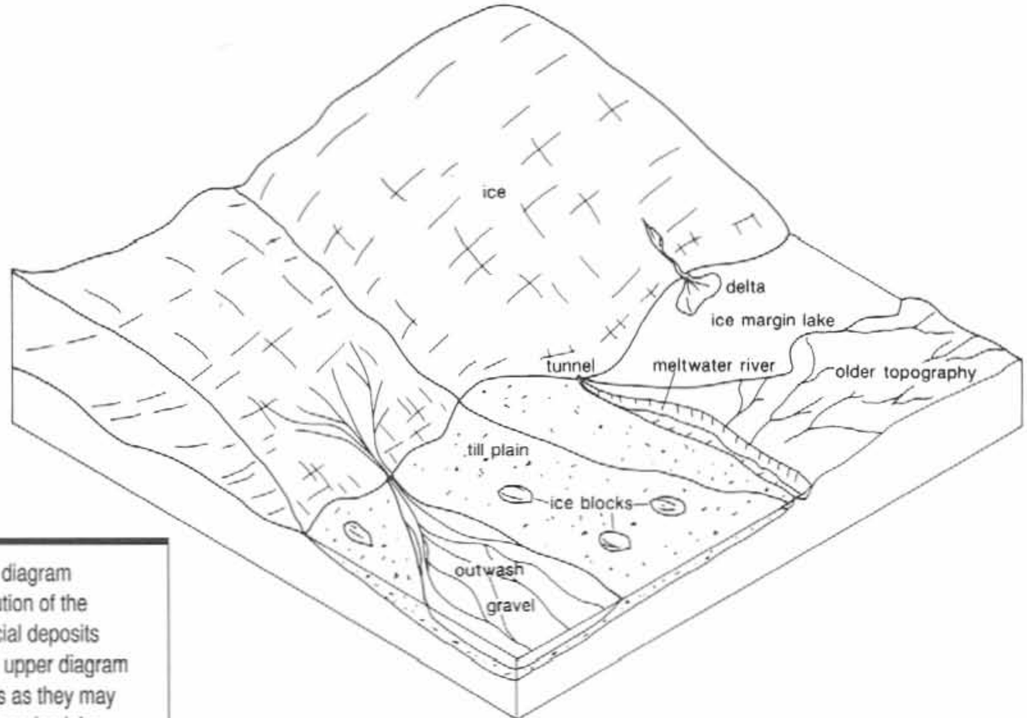
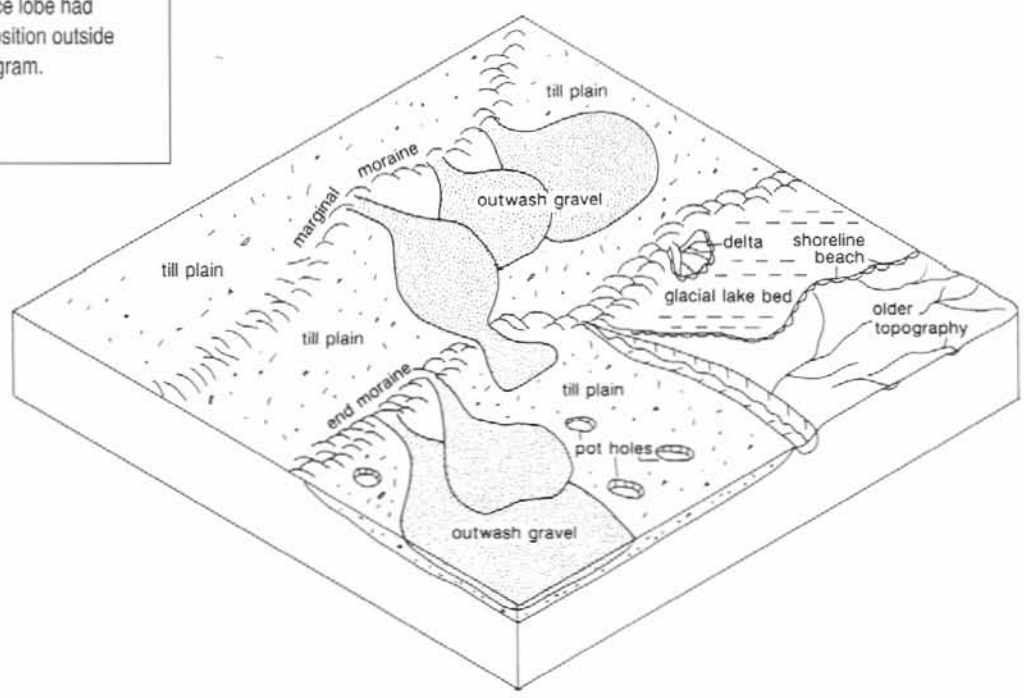
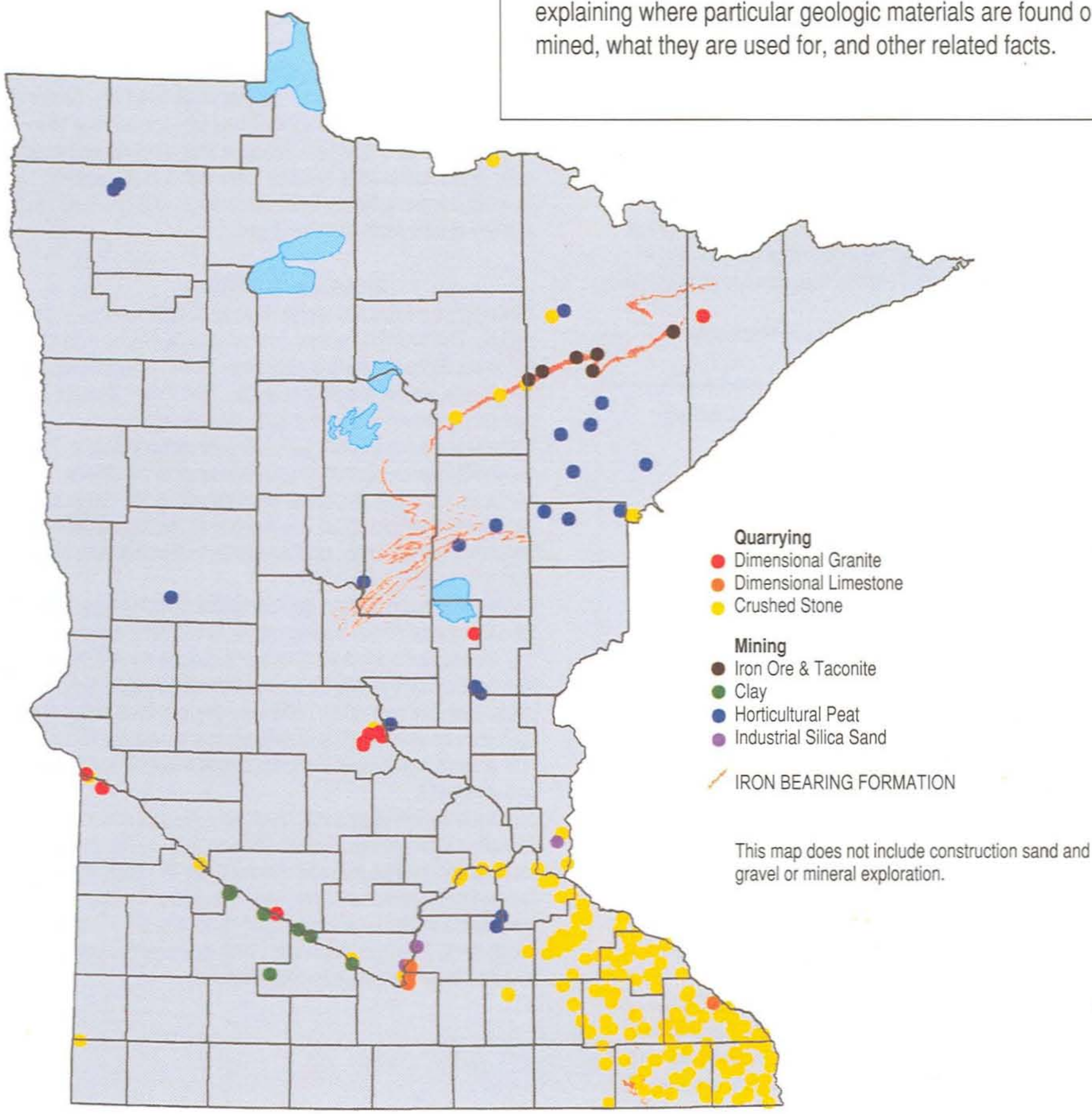


Figure 22—Sketch diagram illustrating the evolution of the more important glacial deposits and landforms. The upper diagram illustrates conditions as they may have been just after an ice lobe ceased to advance. The lower diagram shows the landscape that resulted after that ice lobe had melted back to a position outside the limits of the diagram.



Mineral Industry of Minnesota

Figure 23—Mineral industry of Minnesota map and fact sheet explaining where particular geologic materials are found or mined, what they are used for, and other related facts.



Mineral Industry of Minnesota Fact Sheet

Iron Ore/Taconite

- Minnesota leads the nation in the production of iron ore/taconite. About 75 percent of the nation's production is from Minnesota. (Most of the remaining production is from Michigan.) In 2006, 39 million tons of pellets were shipped from the state.
- Iron ore is probably the single most important nonfuel mineral. Almost all of the higher grade natural iron ore has been mined from Minnesota. Taconite, which is a low-grade iron ore, is mined, crushed, and treated to increase its iron content. Limestone is frequently added. The powdery iron ore concentrate is then processed into hard, marble-sized pellets and shipped to steel mills. The pellets are melted in blast furnaces and then blown with oxygen to make steel.
- Minnesota's first century of iron ore mining has taken place on the Cuyuna, Mesabi, and Vermilion iron ranges, and in Fillmore County. As of 2007, Minnesota iron ore mining is only occurring on the Mesabi Range.
- There are six taconite plants operating in Minnesota:

Mining Company	Plant Location
Hibbing Taconite Company	Hibbing, MN
Mittal Steel USA-Minorca Mine	Virginia, MN
Northshore Mining Company	Silver Bay, MN
Minnesota Ore Operations-Minntac	Mt. Iron, MN
MN Ore Operations-Keewatin Taconite	Keewatin, MN
United Taconite LLC	Eveleth, MN

Industrial Minerals

- Clay is a loose and extremely fine-grained soft rock. Some of its uses include tiles, bricks, and porcelain. The higher grade kaolin clay is used to add the gloss to paper. Companies are currently exploring Minnesota for the higher grade kaolin clay; the principal source in the U.S. is Georgia.
- Silica sand has a high percentage of silica (quartz). It is a raw material for glass and is a source of silicon. Deposits of very well rounded and sorted silica sand grains found in the southeastern part of the state are used in oil drilling to improve the flow of oil to the well.
- Granite and limestone are rocks used in the construction of homes, buildings, and roads. When granite and limestone are shaped into blocks and shipped from a quarry, they are referred to as dimension stone.
- Sand and gravel found in outwash deposits everywhere in the state are used for construction of homes, buildings, and roads.

Peat

- Peat is organic matter formed by the partial decomposition of plant material under saturated conditions. Peat formation occurs only in environments such as bogs and fens, where the rate of production of organic material exceeds the rate of decomposition. The peat mined in Minnesota is primarily used in the horticulture industry, although it is also being used as compost, turkey litter, oil sorbent, and in the removal of base metals from mine seepage.

Impacts of Mining

- Minnesota's mining industries directly employ about 7,700 people. The taconite industry alone contributes over $1 billion annually to the state's economy. Over 1,280 Minnesota companies, which are located in the Twin Cities, Duluth, and the mining areas, supply the taconite industry.
- Recycling is an important part of the minerals industry. The "minimills" use scrap iron to produce steel in electric arc furnaces. Although the amounts of recycling are increasing, mining will continue to be needed due to increased demand, limitations of collection, and impurities in the products available for recycling.
- Environmental protection and compliance with environmental laws are a part of any mining operation. Before there is any new metallic minerals (base or precious metal) mine in Minnesota, there would be an environmental impact statement. This environmental review covers environmental and socioeconomic impacts and alternatives to reduce impacts. The environmental review process invites public participation and comment.
- Statewide reclamation laws govern any metallic minerals operation in Minnesota. Before opening a mine, the company must specify design and operation standards necessary for the protection of human health and the environment and a plan to restore the land after mining is completed. Monetary guarantees, to ensure mine site cleanup and reclamation, are required for all metallic minerals mines.

Glossary of Terms

Agate—Lake Superior agate: Rounded masses of translucent, cryptocrystalline quartz characterized by individual bands having shades of white, gray-orange, brown, or red. Formed in vesicles developed in the tops of lava flow exposed along the shores of Lake Superior but widely distributed in glacial deposits derived from eroded lava flows.

Aggregate: Crushed rock, sand, and gravel, used to mix with cement or bituminous material or for other special construction and manufacturing uses.

Anorthosite: Light-colored, medium- to coarse-grained igneous rock formed at depth and composed mostly of plagioclase.

Anticline: A geologic structure, a fold convex upward whose core contains stratigraphically older rocks.

Asthenosphere: The zone in the earth directly beneath the lithosphere from 70 to 200 km below the surface. The material of the asthenosphere is believed to be soft and yielding to plastic flow.

Atom: The smallest part of an element that can exist alone.

Augite: A common green, brown, or black mineral of the clino-pyroxene family with the general formula (Ca, Na) (Mg, Fe, Al) (Si_2O_6).

Basalt: A dark-colored, fine-grained igneous rock commonly found in lava flows. Basalt contains calcic plagioclase and pyroxene (commonly augite).

Batholith: A mass of igneous rocks > 100 km^2 in surface exposure and composed predominantly of granite or other plutonic rocks.

Bauxite: A mixture of various aluminum oxides and hydroxides commonly found as residual clay deposits in tropical and subtropical regions. The principal commercial source of aluminum.

Biotite: "Black mica." An important rock-forming ferromagnesian silicate having a sheetlike structure.

Catlinite (Pipestone): A special name given to red mudstone quarried at Pipestone National Monument. Catlinite used to produce pipes and other objects by American Indians is commonly called pipestone.

Chert: Chemical sedimentary rock, consisting predominantly of cryptocrystalline to very fine-grained silica (SiO_2).

Clastic: Refers to rocks consisting of broken fragments of older rocks.

Conglomerate: A clastic sedimentary rock consisting of rounded water-worn pebbles cemented together.

Continental crust: The type of crust underlying the continents including continental shelves composed predominantly of granite and related igneous rocks. On average it is about 35 km thick, but maximum thicknesses of 60 km are found beneath mountain ranges.

Convergent plates: Two tectonic plates characterized by movement toward each other.

Craton: A stable relatively immobile area of the earth's crust that forms the nuclear mass of a continent.

Crust: The outermost layer, or shell, of the earth. The earth's crust is generally defined as that part of the earth above the Mohorovicic discontinuity.

Crystal structure: Orderly arrangement of atoms in a crystal.

Dacite: A light-colored, fine-grained, igneous rock commonly found in lava flows or fragmental bodies formed by explosive volcanic processes. Dacite contains sodic plagioclase, hornblende, and some quartz.

Detritus: A collective term for fragmental mineral and rock material (e.g., sand, silt, clay) produced by physical weathering or mechanical erosion.

Dimension stone: Building stone that is quarried and prepared as regularly shaped blocks according to specifications.

Dip: The maximum inclination of strata or other planar features to the horizontal.

Divergent plates: Two tectonic plates characterized by movement away from each other.

Dolomite: A chemically-precipitated, sedimentary rock consisting chiefly of calcium–magnesium carbonate.

Drift: An old term for glacial deposits and especially boulder tills. The term was derived from the belief that boulder tills were deposited by drifting icebergs.

Earthquake: A series of elastic waves propagated in the earth, initiated where stress along a fault exceeds the elastic limit of the rock so that a sudden movement occurs along the fault.

Element: A substance that consists of atoms of only one kind.

End moraine: A ridge of till that accumulates at the terminal margin of a glacier.

En echelon: Geologic features that have a staggered or overlapping arrangement. Strikes of the features individually are oblique to that of the feature as a whole.

Epiclastic rocks: A sedimentary rock in which the fragments are derived by weathering and erosion.

Erosion: Mechanical processes involving changes in wind, water, and temperature that reduce rocks to smaller sizes and flatten topographic relief.

Fault: A fracture or break along which there has been displacement of the two sides relative to one another.

Feldspar: An abundant rock-forming mineral of the general formula (K, Na, Ca) Al $(Al, Si)_3 O_8$, composed of compounds of silicates of calcium, sodium, and potassium. The main types are orthoclase and microcline (potassium aluminum silicate) and the plagioclases albite (sodium aluminum silicate) and labradorite (calcium aluminum silicate).

Fluvial deposit: A sedimentary deposit consisting of material transported and laid down by a stream or river.

Fold: A bend of rock strata or bedding planes resulting from tectonic deformation.

Fossil: The remains of plants or animals preserved in the earth's crust by natural means.

Gabbro: A family of generally dark-colored, medium- to coarse-grained igneous rocks formed at depth and consisting mostly of pyroxene and calcic plagioclase.

Gneiss: A coarse-grained metamorphic rock, mainly granitic in composition, with layers of granular minerals alternating with layers of platy minerals. Some gneisses are marked by alternating light- and dark-colored layers, respectively rich in quartz and feldspar and in dark minerals such as biotite and hornblende.

Graben: A depressed segment of the earth's crust bounded on at least two sides by faults.

Granite: A family of generally light-colored, medium- to coarse-grained, igneous rocks, formed at depth and consisting mostly of quartz and orthoclase or microcline and albitic plagioclase, a potassic/sodic feldspar.

Granitoid: Granitelike in composition.

Graywacke: A loosely defined term referring to a dark sandstone or grit with angular fragments of quartz, feldspar and dark-colored rock, and mineral grains in a more fine-grained "clay" matrix.

Greenstone: An old, but commonly used field term for a dark, fine-grained, basic igneous rock affected by low-grade metamorphism.

Grit: A coarse sandstone. A sedimentary rock consisting of grains 0.5 to 1.0 mm in diameter derived by mechanical erosion from pre-existing rocks.

Ground moraine: Glacial deposits that cover an area formerly occupied by a glacier. They typically produce a landscape of low, gently rolling hills.

Hematite: A mineral consisting of ferric iron and oxygen (Fe_2O_3).

Hornblende: A member of the amphibole family of minerals commonly found as dark-colored crystals in igneous and metamorphic rocks with the general formula $(Ca, Na)_2 (Mg, Fe)_4 (Al, Fe, Ti) (Al, Si)_8 O_{22} (O, OH)_2$.

Hypabyssal rocks: Igneous rocks formed at intermediate depths beneath the earth's surface. They generally occur as tabular-shaped bodies that cut across strata (dikes) or are parallel with strata (sills).

Ice Dome: Local parts of an ice sheet where the ice is especially thick.

Ice lobe: A restricted flow of ice away from an ice sheet.

Ice sheet: A thick extensive body of glacial ice that is not confined to valleys.

Igneous rock: A rock formed by solidification from a molten or partly molten state.

Intrusion: A body of igneous material that invades older rock.

Iron-formation: A chemically-precipitated, sedimentary rock consisting of silica and more than 15 percent total iron.

Island arcs: A chain of volcanic islands. Islands arcs are generally convex toward the open sea.

Isotope: One of two or more, radioactively stable or unstable, atomic species of a chemical element, namely, a species of an element having the same number of protons in the nucleus but having a different number of neutrons.

Kaolin clay: A fine, usually white, clay consisting mostly of alumina and silica.

K–feldspar: A general term for the three different structural types (microcline, orthoclase, and sanidine) of potassium feldspar.

Laterite: A soil that is rich in oxides of iron and aluminum formed by deep weathering in tropical and subtropical areas.

Lava: Magma that reaches the earth's surface. Synonymous with extrusive rock.

Limestone: A chemically-precipitated, sedimentary rock consisting chiefly of calcium carbonate.

Lithosphere: The relatively rigid, outer zone of the earth including the continental crust, the oceanic crust, and the upper part of the mantle.

Magma: Molten rock generated within the lithosphere or subjacent mantle; the parent of all hypabyssal and plutonic rocks.

Mafic rock: A general term for an igneous rock mostly composed of dark-colored minerals.

Mantle: The zone of the earth's interior between the base of the crust and the core.

Metamorphic rock: A rock formed by the actions of heat and pressure. The alteration of an earlier formed rock generally by the formation of new minerals, but without the occurrence of melting.

Mica: A mineral group composed of phyllosilicates (i.e., silicates with sheetlike substructures) with the general formula, $(K, Na, Ca) (Mg, Fe, Al)_{2-3} (Al, Si)_4 O_{10} (OH, F)_2$.

Migmatite: Mixed rock, composed of two distinct components—a darker and older of metamorphic materials and a lighter and younger of igneous or igneous-looking materials.

Mineral: Naturally-occurring, inorganic, crystalline solid whose physical and chemical properties vary within established limits.

Mohorovicic discontinuity: The boundary surface that separates the earth's crust from the subjacent mantle; its depth varies from about 5–15 km beneath the ocean floor to about 30 to 50 km below the continents or as much as 70 km beneath some mountain ranges. Commonly referred to as the Moho.

Mudstone: A sedimentary rock consisting mostly of clay-size grains that lack lamination or layering.

Muscovite: "White mica." An important rock-forming mineral that has a sheetlike structure. A predominantly potassium-aluminum silicate.

Normal fault: A steeply dipping fault where the displacement of strata is downward on the fault plane.

Oceanic crust: The type of crust that underlies the ocean basin. It is about 5 km thick and composed predominantly of basalt.

Outwash: Stratified sediment washed out from a glacier by meltwater streams and deposited in front of an end moraine.

Passive margin: A lithospheric plate margin where crust is neither created nor destroyed.

Pillow basalt: Igneous, extrusive volcanic rock, solidified in a subaqueous environment to form discontinuous pillow-shaped masses generally 30 to 60 cm across.

Pluton: A deep-seated, igneous intrusive rock mass.

Plutonic rock: An igneous rock formed deep beneath the earth's surface.

Pyroxene: A family of igneous and metamorphic minerals having the general formula $(Ca, Na, Mg, Fe) (Mg, Fe, Al) (Si, Al)_2O_6$. A common pyroxene is the mineral augite.

Quartz: The commonest naturally-occurring variety of silica (silicon dioxide). Quartz is an essential component of many igneous and metamorphic rocks and sand grains are commonly fragments of the mineral.

Quartzite: Either a metamorphic rock in which the quartz grains of a sandstone have recrystallized under heat and pressure to form an interlocking mass (metaquart-zite) or a quartz-rich sandstone that has been cemented by silica (orthoquartzite).

Regression: Converse of transgression. A change that shifts the boundary between marine and non-marine deposition or the boundary between marine deposition and erosion inward toward the center of a depositional basin. The gradual emergence of land due to the withdrawal of seawater.

Relief: Changes in the elevations of a land surface. Abrupt changes in relief are most notable.

Reverse fault: A steeply dipping fault where the displacement of strata is upward on the fault plane.

Rift system: A system of elongate, fault-bounded basins having a en echelon arrangement and resulting from extension. Synonymous with graben.

Rock: An aggregate of minerals that forms an appreciable part of the lithosphere.

Sag basin: A broad, shallow depression in which sedimentary material can accumulate.

Sandstone: A sedimentary rock consisting of sand-size (1/16–2 mm) grains derived by mechanical erosion from pre-existing rocks.

Schist: Medium- to coarse-grained metamorphic rock with a strong foliation defined by the preferred direction of oriented mineral grains such as biotite, muscovite, and hornblende, making up 50 percent or more of the rock.

Sedimentary rocks: A class of rocks formed either by the weathering, erosion, and deposition of earlier formed rocks or by chemical precipitation.

Shale: A laminated, sedimentary rock consisting mostly of clay-size grains.

Siderite: A mineral consisting of ferrous iron and the carbonate radical ($FeCO_3$).

Spreading ridge: Suboceanic zone where magma rises between two crustal plates as they separate.

Strike-slip fault: A steeply-dipping fault where the displacement of strata is parallel to the fault plane. Synonymous with sheer fault.

Subduction zone: Zone where one crustal plate overrides another plate along a convergent margin.

Superposition: The assumption that in a sequence of undisturbed sedimentary layers, the ones lying above are successively younger than those lying below. The concept is generally referred to as the Law of Superposition.

Syncline: A geologic structure. A fold convex downward whose core contains stratigraphically younger rocks.

Taconite: Low-grade iron-formation (FeO–Fe_2O_3 about 17–30 percent) of which magnetite is mechanically separated and concentrated. The ore is commonly fused into marble-size spheres generally referred to as taconite pellets.

Tectonic: A term pertaining to the forces involved in, or the resulting structures of features produced by the motion of colliding plates.

Terrane: A faulted-bounded segment of the earth's crust that has unique rocks and structures that serve to distinguish it from adjoining terranes.

Thrust fault: Low-angle, reverse fault along which there has been a substantial component of horizontal displacement.

Till: Unsorted and unstratified glacial deposits.

Topographic: Refers to the configuration of the earth's surface including its relief and the placement of natural and man-made features.

Transgression: Any change that shifts the boundary between marine and non-marine deposits or the boundary between deposition and erosion outward from the center of a depositional basin. The encroachment of large landmasses by seas.

Troctolite: A family of dark-colored, medium- to coarse-grained, igneous rock formed at depth and composed mostly of olivine and plagioclase.

Unconformity: A discontinuity in the succession of rocks containing a gap in the geologic record. A surface of erosion or nondeposition.

Vesicles: Small holes formed in a volcanic rock by gas bubbles that became trapped as the lava solidified.

Volcanic arc: A curved belt of volcanoes above a subduction zone where crustal plates converge.

Volcanic rocks: Magma and associated gases transferred from the earth's interior to the surface.

Acknowledgments

The following sources were consulted for illustrations.

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Figure 3—Modified from unnumbered cover illustration for "Geofluids Brochure," Department of Geology and Geophysics, University of Minnesota, 6 p.

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Publication design by the Bureau of Information and Education, Department of Natural Resources.

Fifth Printing 2007

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