Appendix

Appendix A. Geology of Minnesota

"Geology is the study of the planet Earth - the materials of which it is made, the processes that act on these materials, the products formed, and the history of the planet and its life forms since its origin." (Bates & Jackson, 1987). It is evident from such a definition that geology encompasses a wide range of studies. In the Geotechnical Engineering Section, we attempt to identify, classify and quantify earth materials as we encounter them in planning, construction and maintenance of our state highway system. Some of the basic objectives of geotechnical investigations are to define the nature, characteristics, properties, thickness, and lateral extent of bedrock and overlying soils as well as ground water conditions within a given project area. To gain an understanding of the materials with which we work, whether they are rock, soil, or intermediate geomaterials, it is important to have some knowledge of their geologic origin, and how subsequent geologic processes have altered them.

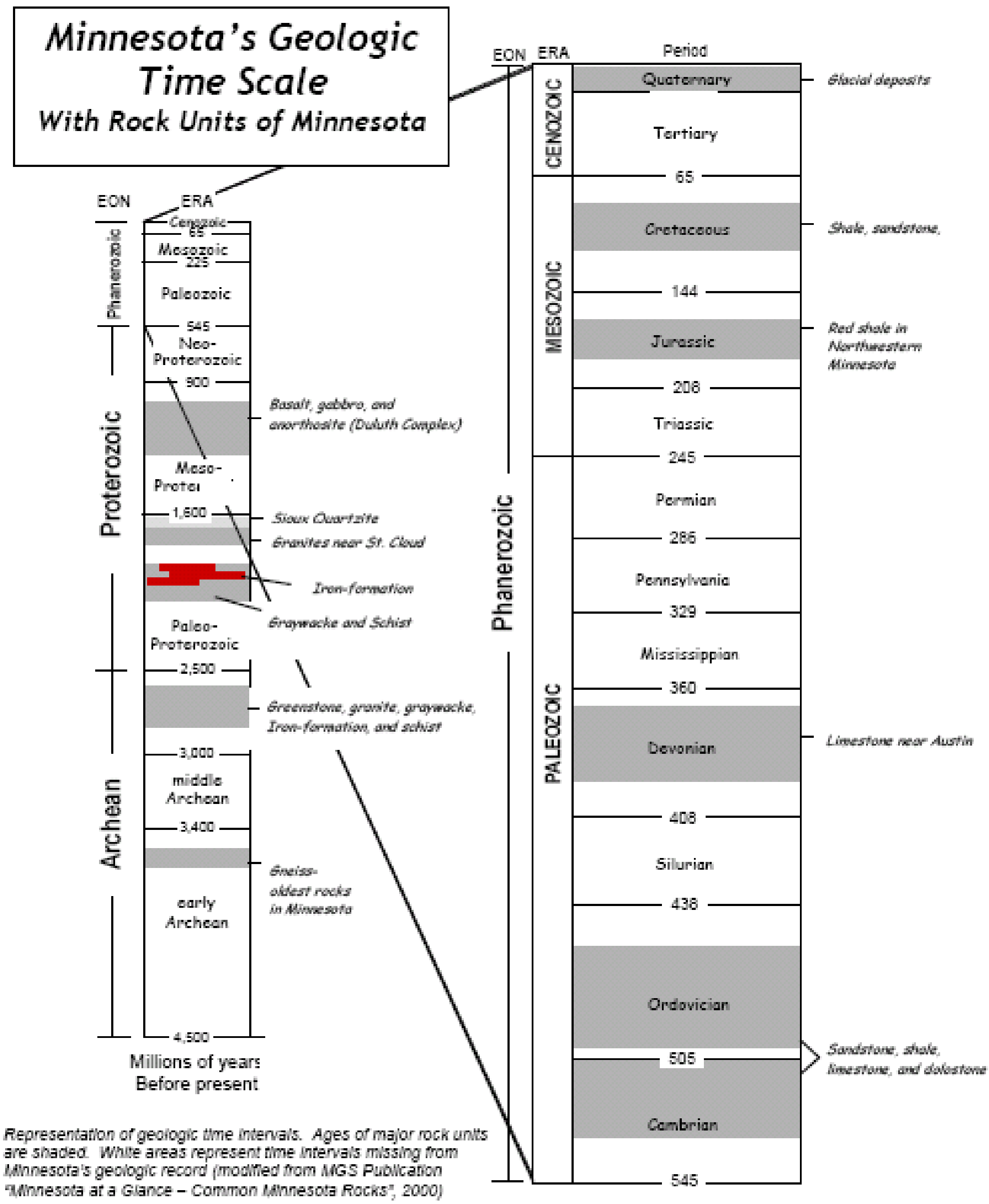
A Brief Overview

The geology of Minnesota is both complex and diverse. The geologic history includes periods of mountain building and subsequent erosion, folding and faulting, a near tearing apart of the continent, extensive volcanism, and submersion by epicontinental seas with subsequent deposition of thousands of feet of sedimentary rocks. All of these events took place prior to the start of the Quaternary Period, which began about two million years ago. The bedrock skeleton that was created over eons of time is buried in all but the southeastern and northeastern portion of the state by more recent, unconsolidated Quaternary deposits. During the Quaternary Period, moving, and melting, glacial ice significantly altered the landscape. This chapter will briefly describe some of the significant geologic events that took place over the eons of time since the first rocks in the state were formed.

Geologic Time

Geologic history has been subdivided into units of varying magnitude, which together comprise the geologic time scale of earth history (Figure A-1).

Figure A-1: Geologic Time Scale



Workers in Western Europe and Great Britain delineated the major units of time during the nineteenth century, thus certain names are based on those locations, such as Cambrian, from Cambria, which is the ancient name for Wales (a region in Great Britain). The relative time scale is divided into eons, eras, periods, and epochs, in order of decreasing magnitudes of time. Rocks of the **Phanerozoic eon** contain abundant, easily recognizable fossils. This eon comprises virtually the entire record of advanced life. The name Phanerozoic is derived from the Greek words meaning “visible life”. This eon is divided into the **Paleozoic**, **Mesozoic**, and **Cenozoic eras**, on the basis of the fossil content of rocks deposited during those times. The boundaries of these eras are marked by major changes in the presence of life forms. The **Paleozoic era** was the age of shelled marine organisms, primitive fish, amphibians, reptiles and plants (now extinct). Paleozoic is the Greek word for “ancient life”. The **Mesozoic era** (“middle life”) was the age of reptiles (the best known being the dinosaurs) and the invertebrate ammonite (ancient relative of the modern nautilus and squid). The **Cenozoic era** (“recent life”) is the age of mammals and flowering plants.

Geologic History of Minnesota

Geologic time is immense in its duration - It is amazing to think that rocks that were created over 3½ billion years ago are still found in the state, and in good condition. Geologic processes take an extremely long time; the state’s geologic history has aptly been described as one of *“long periods of boredom punctuated by moments of terror”* (Green 1996). In other words, great mountain-building events and rifting of the continent occupied only a small portion of Minnesota’s geologic history. The remaining expanse of time was consumed by erosion, the slow, methodical wearing down of these mountains by wind, rain and ice.

The geologic history of the state can be divided into two categories; 1) the **bedrock history**, which encompasses the immense period beginning with the cooling and solidification of the planet and ending with the retreat of the last shallow sea in the western half of the state. This four billion year plus time-period is the length of time that it took to form our present-day bedrock skeleton. See Figure 10-15 for a simplified bedrock geologic map of Minnesota. The second category would be, 2) the **glacial history** of the state, which encompasses only the last two million years. Though this period covers very little time by comparison to the bedrock history, it did as much in terms of shaping our present-day landscape and providing aggregate and groundwater resources, as the preceding four billion years.

Bedrock History

No one knows for sure how or when the oldest rocks in the state were created. They belong to a central core of the North American continent known as the Canadian Shield. The Earth is believed to be about 4½ billion years old, yet the oldest rocks found in the world thus far are only 3.8 billion years old. It is interesting to note that the gneisses in the Minnesota River Valley have been determined to be approximately 3.6 billion years old, which makes them some of the oldest rocks on the surface of the earth.

Precambrian Time

Much of Minnesota's bedrock base was formed during Precambrian Time. The Precambrian, as a whole, represents approximately eighty-seven percent of geologic history spanning from roughly 4.6 billion years ago to the beginning of the Paleozoic Era, approximately 545 million years ago. The basis for the division between Precambrian and the Paleozoic was originally placed at the point that scientists thought was the beginning of life on the earth. Since the establishment of the boundary, some simple forms of life, such as algae, have been found in the Precambrian, but the real explosion and diversification of life forms occurs at the beginning of the Paleozoic Era. The great span of Precambrian time is divided for convenience into two major parts - the Archean and the Proterozoic.

Archean Eon

While the Archean Eon lasted from 4.6 to 2.5 billion years ago, the oldest rocks in Minnesota are gneisses from the Minnesota River Valley, which have been dated at around 3.6 billion. Thus, approximately one billion years of Minnesota's geologic history has been lost in obscurity. Some possible explanations may include; early meteorite bombardment which obliterated any remnants of this original material, intrusion of magma (molten rock material) that metamorphosed (changed) the material, or it could be that these rocks still exist but are simply located at inaccessible depths. Nonetheless, Early Precambrian-aged rocks in Minnesota consist primarily of material younger than this 'lost' material and belong to the **Canadian Shield** (Figure A-2).

Figure A-2: Limits of Canadian Shield rocks (shaded).

The Canadian Shield, which is the nucleus of the North American continent, contains dozens of belts or strips of volcanic and sedimentary rocks. It is unknown if the rocks were originally deposited in these elongate patterns or if they are the result of subsequent crustal movements. In any event, it appears that fissures began to open up in the old preexisting gneissic terrain, through which basaltic lava flowed out. Much of this lava was deposited under water as evidenced by the **pillow structure**. Accumulations of up to 15,000 feet (4,575 meters) thick are believed to have been deposited in Minnesota. Through this thickness of lava flows, additional eruptions continued, only this time with more volatile rhyolitic magma. These eruptions were more explosive, similar to modern-day continental volcanoes that eject large amounts of pyroclastic material. As the volcanic deposits continued to pile up, especially as they grew above sea level, weathering and erosion worked between volcanic events to produce sediments that became mixed and interlayered with the volcanics.

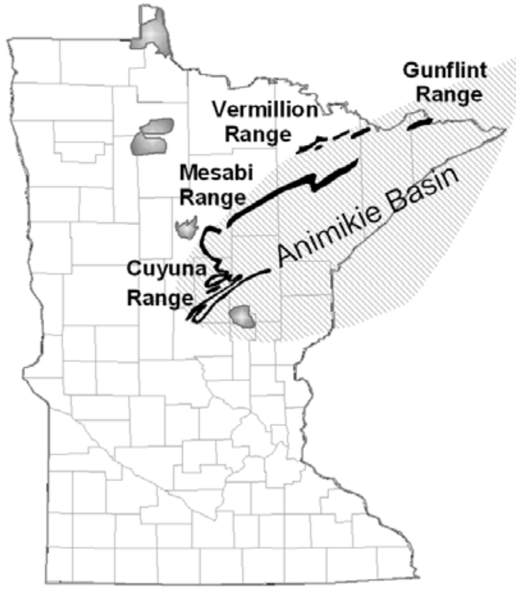
After cessation of volcanic activity, the volcanic-sedimentary deposits were subjected to intense folding, accompanied by intrusion of granitic magma. The magma rose into the volcanic-sedimentary pile where it solidified at least a mile below the surface, as evidenced by its coarse texture. As the granites rose, the nearby volcanic and sedimentary rocks sank, giving the “belt” appearance described above. The granites metamorphosed the volcanic and sedimentary rocks with which they came in contact. The pillow basalts, containing the dark minerals plagioclase, olivine and pyroxene had these minerals altered to predominantly green-colored minerals; chlorite, epidote and actinolite. The resulting metamorphosed basalt (or metabasalt) is commonly known as **greenstone**.

Not long after solidification of the granitic intrusions, about 2.7 billion years ago, the greenstone-granite terrain was subjected to new stresses that caused movement along numerous faults. Great blocks of the earth’s crust were moved up or down relative to adjacent blocks. This combination of folding, intrusion, and faulting produced mountain ranges throughout northern Minnesota and the rest of the Canadian Shield. The Algoman Mountains are estimated to have been up to several miles high, with similar depths below the surface of downfaulted material. This mountain-building episode of 2.7 billion years ago is called the **Algoman Orogeny**.

Proterozoic Eon

The Proterozoic Eon spans 1.9 billion years from 2.5 billion to 545 million years ago. The *early* Proterozoic Era extends from the end of the Algoman mountain-building episode to shortly after the end of another mountain-building event, the Penokean Orogeny, about 1.85 billion years ago. Most of the *early* Proterozoic rocks are sedimentary, deposited in a shallow sea on top of the eroded Archean basement in an area referred to as the **Animikie Basin**. Rocks of this age are found in east central and northeastern Minnesota in a basin now bounded by the iron-formations of the Mesabi, Gunflint, and Cuyuna ranges (Figure A-3).

Figure A-3: Animikie Basin with Minnesota Iron Ranges



Sediments made up of quartz-rich sand were deposited along the shoreline, followed by iron-rich layers and eventually a great thickness (thousands of feet) of fine-grained clays, silts, and dirty sands as the basin deepened. The quartz sand became quartzite, the iron-rich deposits developed into the various iron-formations, and the fine-grained materials became shale and graywacke. The accumulation of sediment in the Animikie Basin ended when a great thrusting movement shoved part of the mid-continent to the north toward the basin. This crustal deformation is known as the **Penokean Orogeny**, and has been dated at about 1.8 billion years ago. This intense, northward-directed pressure folded the shale and graywacke of the southernmost unit (Thomson Formation) and induced the development of rock cleavage as the shale was metamorphosed to harder slate. At the heart of this orogeny was the intrusion of the granites and granodiorites found in the central portion of the state (St. Cloud area). These intrusive rock bodies were at the core of a Penokean mountain range.

The beginning of the *middle* Proterozoic Era is marked by erosion of the Penokean Mountain range. Sand-rich sediment from these mountains as well as the old Algoman Mountains was transported by rivers and streams to low areas (basins) in southwestern and northeastern Minnesota. In southwestern Minnesota this thick deposit, up to 5,000 feet (1,525 meters) thick, became the Sioux Quartzite. This quiet erosional period was interrupted about 1.2 billion years ago when the continent began to spread apart, creating a rift extending from the middle of Lake Superior to Kansas. This great zone of fracturing and crustal thinning is known as the **Midcontinent Rift System** (Figure A-4).

Figure A-4: Midcontinent Rift System containing basalts that were extruded during a splitting apart of the continent approximately 1.2 billion years ago (After Ojakangas & Matsch, 1982).

As a result of this activity, lava poured out onto the surface in thousands of individual flows. The total thickness of lava deposited along the North Shore of Lake Superior (from Duluth to Grand Portage) is in excess of 25,000 feet (7,620 meters). The lava flows are of predominantly basaltic composition and make up the **North Shore Volcanic Group**. This period of eruption and rifting continued for a few million years and then abruptly ended. If the rifting had continued a new ocean basin might have been created, which would have put Minnesota and Wisconsin on opposite shores.

Subsidence continued for several more millions of years as large amounts of sediment accumulated in these low areas. As much as 15,000 feet (4,570 meters) of sedimentary rock accumulated in the center before the sinking ceased. These sedimentary rocks include the **Hinckley** and **Fond du Lac** sandstones exposed in the St. Croix River Valley and along the St. Louis River, as well as the Solar Church Formation, which is not exposed in outcrop.

Immediately following the rifting and volcanic activity, large bodies of magma continued to rise toward the crust but became trapped at various levels and cooled slowly in place to form coarse-grained intrusive rocks. The largest of these intrusive bodies is known as the **Duluth Complex**. It extends in an arch-shaped body along the entire length of the North Shore Volcanic Group, extending nearly as far west as the iron range. These coarse-grained igneous rocks can be found in proximity to the fine-grained lava flows in the arrowhead region, and even though they are chemically similar in some cases, their engineering properties (both as aggregate and as a structural element) may vary significantly.

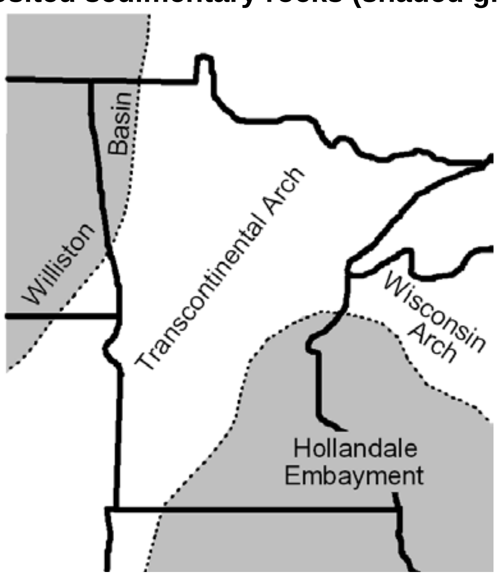
Figure ???, included at the end of this chapter, shows a stratigraphic succession of Precambrian rocks in Minnesota.

Paleozoic Era

During the early Paleozoic Era (beginning about 545 million years ago), shallow marine seas invaded the interior of North America several times and deposited relatively thin layers of sandstone, shale and carbonates on the eroded Precambrian basement rock. The seas invaded low areas in both the northwestern and southeastern corners of the state. In the southeastern portion of the state, the depression is known as the **Hollandale Embayment** and is shaped somewhat like a bowl**,** with the center located nominally under the Minneapolis Campus of the University of Minnesota. The low area in the northwestern corner was the eastern-most extent of the **Williston Basin**, which occupied North Dakota and much of southern Alberta, Canada (Figure A-5).

Deposition of sediments began in the Hollandale Embayment in the Early Cambrian Period primarily as beach sands, which produced formations such as the Mt. Simon, Franconia, and Jordan Sandstone. In this basin, sediments continued to accumulate through the Ordovician Period (505 to 438 million years ago),

Figure A-5: Shallow depressions during the Paleozoic Era where shallow seas deposited sedimentary rocks (shaded gray).



but due to changes in the depositional environment, carbonates were now the principal product. The Ordovician seas produced the Shakopee and Oneota Formations (together known as the Prairie du Chien Group), as well as the Galena Group (Stewartville, Prosser and Cummingsville limestones), all of which are relied upon heavily for aggregate production in the southeastern portion of the state. Sometime near the end of the Ordovician Period, around 438 million years ago, the seas retreated from the area marking a period of non-deposition and erosion throughout the Silurian Period and part of the early Devonian. Another northward advance of the seas occurred during the Middle Devonian, roughly 380 million years ago. Carbonates were swiftly deposited during this brief advance and abruptly retreated by the end of the Devonian Period (360 million years ago). This retreat marked the final appearance of seas from the Hollandale Embayment, which was responsible for the deposition of roughly 2,000 feet (610 meters) of sedimentary rock in the Twin Cities.

Deposition of sediments in the northwest corner of the state occurred on a much smaller scale. The sea that occupied the Williston Basin began to spill over into the state in the Ordovician Period. During the 70 million years of the Ordovician, about 450 feet (135 meters) of sedimentary rock, predominantly carbonate, was deposited. At the end of the Ordovician Period, the sea retreated, and there is no evidence of further deposition in the area until the Jurassic Period, some 230 million years later. Little is known about the Jurassic rocks in northwestern Minnesota, since they are buried by glacial drift, but drilling indicates that they are as much as 100 feet (30 meters) thick, and consist of red mudstone with minor amounts of carbonate.

There is no evidence of rocks in Minnesota from the Mississippian, Pennsylvanian or Permian Periods, a sequence of 125 million years. During this time it is believed that Minnesota persisted above sea level, though it is possible that the state may have received some deposition which has either been eroded, or has yet to be discovered. Thus ends the record of the Paleozoic Era.

Mesozoic Era

Just as the Paleozoic Era ended with the state above sea level, so began the Mesozoic (245-65 million years ago). There are no known rocks of Triassic Age (245 to 208 million years ago) in the state. As mentioned previously, there was a limited deposit of Jurassic sediment in the extreme northwest portion of the state, but the remainder of Minnesota was unaffected. The last major invasion of seas in Minnesota took place beginning about 100 million years ago, during the Cretaceous Period. The sea apparently covered most of the western half of the state with a quite irregular shoreline. This shallow sea extended as far west as Idaho and Utah, and was responsible for bringing a warm, subtropical climate to Minnesota and much of the remaining continent to the east. The shallow sea and warm climate were responsible for placing deposits of poorly lithified siltstone, shale, and sandstone, as well as for deep chemical weathering of the remaining exposed bedrock. In the Minnesota River Valley, the Archean-aged granites and gneisses were weathered to a soil-like condition, rich in kaolinite. The kaolinite deposits are mined for use in pottery and the production of cement. The final “liquid” sea remained until the end of the Cretaceous Period (65 million years ago).

Cenozoic Era

The rise of the Rocky Mountains to the west during the Tertiary Period (65 to 2 million years ago) brought all the land between there and Minnesota above sea level for the final time (we hope). During this high and dry period either sediments did not accumulate or were subsequently eroded because no rocks representing the Tertiary time period have been found in Minnesota. The rise of the Rocky Mountains also put an end to the luxurious subtropical climate of the Cretaceous Period. Minnesota would now slowly begin to achieve its reputation as the “icebox of the nation.”

Glacial History

In the later stages of the Cenozoic Era, about two million years ago, the warm stable climate had begun to deteriorate. It was replaced by a climate with cyclical variation, fluctuating between cold and warm periods. During the cold periods, or “Ice Ages”, large quantities of snow accumulated in Canada which built up to create a large continental ice sheet known as the **Laurentide Ice Sheet** (Figure A-6). See the end of this chapter for a map of the Quaternary Geology of Minnesota.

Figure A-6: Extent of ice during the last glacial advance (Wisconsin). Dashed lines represent increased continent size due to lowering of sea level.

Continued accumulation, often lasting tens-of-thousands of years, resulted in the slow methodical advance of the ice sheets across the northern tier of states in the United States. The warm “temperate” cycles led to a melting of the glacial ice causing the leading edge of the ice sheet to retreat northward. These cycles apparently occurred multiple times on a worldwide basis, and Minnesota (as we now know it) did not escape its influence. The complex nature of the surface deposits resulting from glacial activity indicates that Minnesota experienced a minimum of four periods of major ice coverage.

Although the glacial history and stratigraphy of Minnesota have been studied since the late 1800's, little is known about the nature of the earlier glacial periods in the state, because few representative deposits survived the subsequent ice advances. However, ample surface deposits document the most recent glacial phases (Late Wisconsin) and much of Minnesota’s present landscape is the direct result of this activity. The abundant exposures are helpful for determining the glacial history of the state.

The time period during which glacial ice covered most of the state is referred to as the **Pleistocene Epoch**. The four major glacial stages were as follows:

Table A-1: Glacial Stages of Minnesota

Glacial Stage	**Years Ago**
Wisconsin	75,000 to 12,000
Illinoian	550,000 to 400,000
Kansan	1,400,000 to 950,000
Nebraskan	2,000,000 to 1,750,000

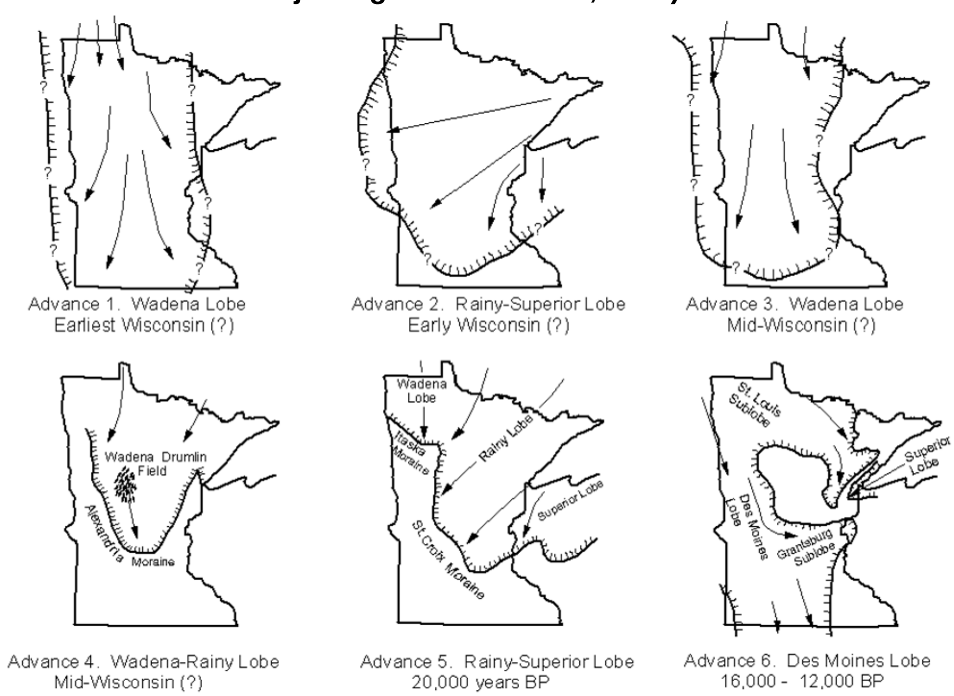
During the most recent Wisconsin Glacial Stage, there were two distinct ice accumulation centers to the north of Minnesota; one in the province of Manitoba, Canada; the other near Hudson Bay. At these centers ice amassed to such great thickness that it actually coalesced, and invaded, or “flowed”, into the state. Minnesota’s pre-glacial topography played a primary role in dictating the flow dynamics of the ice entering the state from these centers. Preexisting highlands tended to split the ice sheet into distinct “lobes”, and valleys tended to localize the flow. The major topographic features that controlled the region's ice advances include the Lake Superior basin and the Laurentian divide in northeastern Minnesota, and the Red River Valley and the Red Lakes Lowland in western and central-northern Minnesota, respectively.

The southern margin of the ice sheet often exhibited a lobate shape as it repeatedly advanced into, and retreated from Minnesota. Channeled by topography, each lobe tended to flow into distinct regions of the state, and each contained ice with a unique mixture of soil, sediment and rock particles that gave it a characteristic compositional fingerprint. Researchers can therefore determine the glacial history by the compositional and stratigraphic (vertical and horizontal position) nature of the deposits created as the ice melts away.

Major Ice Lobes

The major ice lobes that traversed the state during the last glacial stages include the Superior lobe, Rainy lobe, Wadena lobe, and the Des Moines lobe (Figure A-7). Two branches, or sublobes, of the Des Moines lobe have also been identified: the St Louis and the Grantsburg sublobes. The lobe names indicate the region that each invaded, or the area of its farthest southern extent. It is difficult to reassemble some of the early Wisconsin advances, but it appears that the state was first traversed by the Wadena Lobe, followed by a Rainy-Superior Lobe, in earliest Wisconsin time and then by a combination of Wadena and Rainy Lobes during mid-Wisconsin and then again by the Wadena Lobe. Finally, in late-Wisconsin time, the Superior and Rainy Lobes pushed over a retreating Wadena Lobe, and were then overridden by the late-coming Des Moines Lobe. The lobe directions are significant to the state, because each lobe brought with it an incredible volume of soil and broken rock from the area it traversed. A brief description of each lobe is given below, in order of their appearance in the state.

Figure A-7: Summary of ice activity during the Wisconsin glaciation as reconstructed from the distribution of glacial sediments and landforms (after Ojakangas and Matsch, 1982)



a) Wadena lobe

The Wadena lobe takes the name of the county in west-central Minnesota where, nearby, it deposited considerable amounts of glacial material. The exact limits of the Wadena lobe are poorly defined, as much of its deposits are masked by debris from later advances of the Superior, Rainy and Des Moines Lobes. However, Wadena Lobe deposits have been traced as far south as South Dakota and Iowa. Most interpretations suggest that Wadena lobe ice emerged from the north or northeast and traveled south and southwest. Wadena lobe deposits are generally calcareous and contain abundant limestone particles, which are generally considered to be D-cracking susceptible in concrete pavements.

b) Superior Lobe

The Superior lobe is so named because the Lake Superior Basin consistently channeled this ice emanating from the north-northeast. The Superior lobe moved from northeast to southwest, and characteristic deposits in and around the Twin Cities area indicate that Superior lobe ice made it at least that far south. Superior lobe deposits are typically reddish brown, non-calcareous, and contain abundant volcanic rocks from the North Shore of Lake Superior.

c) Rainy lobe

This lobe gets its name from the Rainy Lake region in extreme north-central Minnesota, and like the ice of the Superior lobe, its regional flow directions were from northeast to southwest. However, the Rainy lobe advanced across the relatively high ground between Lake Superior and the Red Lakes Lowland, and extended at least to the present-day Mille Lacs region. Deposits of the Rainy lobe are typically brown and non-calcareous, and often contain a variety of igneous and metamorphic rock fragments from locally derived bedrock as well as Canadian Shield bedrock.

d) Des Moines lobe

The Des Moines lobe is named for its maximum southern position at present-day Des Moines, Iowa. The Des Moines lobe was active relatively late during Minnesota's glacial history, and it differs from the Superior and Rainy lobes in that it originated from the northwest. As the Des Moines lobe flowed to the south-southeast, it generally followed the Red River Valley, Minnesota River Valley, and the low-lying areas of southwestern Minnesota. Des Moines lobe deposits are often gray, highly calcareous, and rich in fragments of Pierre shale from Canada and North Dakota.

e) St. Louis & Grantsburg sublobes

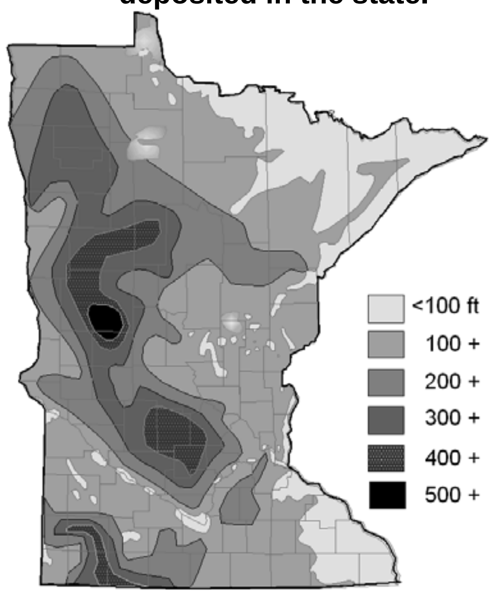
These sublobes are similar in that they apparently originated as separate offshoots of the Des Moines lobe. Deposits from both sublobes are calcareous, but the St. Louis sublobe does not contain as much shale as either the Grantsburg sublobe or the parent Des Moines lobe. From northwestern to north-central Minnesota, the St. Louis sublobe flowed east across the Red Lakes Lowland toward present-day Koochiching County, with a small sub-lobe penetrating south reaching the northern edge of Mille Lacs Lake. It first incorporated clays from proglacial lakes and then assimilated minor quantities of Rainy lobe debris. The Grantsburg sublobe diverged from the Des Moines lobe considerably farther to the south, in the west central to southwestern part of the state. This ice flowed east-northeast and invaded regions vacated by retreating

Superior lobe ice. It traversed the present-day Twin Cities area and eventually reached the Grantsburg, Wisconsin area. As Grantsburg ice overrode the Superior and Rainy lobe deposits, it incorporated some of the debris. Grantsburg sublobe deposits often differ in color and composition from those of the St. Louis sublobe since the Grantsburg deposits often contain debris derived from older Superior and Rainy Lobe deposits.

f) Glacial Depositional Features

Near the edges of the glaciers, where melting was considerable, thick deposits of **drift** (any glacial related deposit) were left behind. Abundant glacial drift deposits, some more than 600 feet (180 meters) thick, cover the face of Minnesota (Figure A-8). Drift can be conveniently divided into either of two broad classifications: **sorted** and **unsorted.**

Figure A-8: Drift Thickness Map representing approximate thickness of drift deposited in the state.



g) Unsorted material

Till is the unsorted material deposited directly by the ice. It can be laid down on the underlying material beneath the bed of the glacier or deposited by the melting away of the dirty ice in which it is entrained. Till is unsorted material ranging in size from clay particles to boulders. Its overall texture typically ranges from clay loam to sandy loam; with the clayey tills often exhibiting high blow counts (standard penetration test) due to over-consolidation by the extreme weight of the overriding glacial ice. Since the deposits are not sorted, they are of little value to aggregate producers. Till can be found as the principle component of several different glacial landforms, such as **end moraines**, **ground moraines,** and **drumlins**:

End moraines mark the farthest extent of a glacier. At the margins of glacial ice, accumulation of debris can be immense as the forward progress of the glacier mass stagnates; yet internal movements continue to bring material forward. The associated landform is a broad ridge that often exhibits a hummocky surface and clusters of lakes. Most moraines are aggregate-poor, but it is often possible to find a sorted deposit buried somewhere in the deposit.

Ground moraines are composed of till dropped during a glacial advance or deposited by a retreating glacier as a thin blanket marked by low hills and swales.

Drumlins are formed when ice moves over existing glacial deposits and remolds the older till into elongated hills with their long axis parallel to the direction of ice movement. Drumlins typically occur in swarms, often referred to as "fields" and are found predominantly in the central region of Minnesota.

h) Sorted Material

Outwash is glacial sediment that has been transported and deposited by melt waters from a glacial source. The energy of the melt water stream will determine the size of particles it can carry, therefore, outwash tends to be sorted, with the finer particles separated from the coarser ones. Just as till is the major component of several different glacial landforms, so also is outwash. Outwash can be found in broad plains (**outwash plains**) that cover many square miles, or it can be confined to narrow valleys either above ground (such as **eskers**) or below ground (such as **tunnel valleys**). **Glacial lakes** fit loosely under the definition of outwash, since they contain sediment that is well-sorted and derived from glacial activity. These are some of the significant glacial landforms that are composed of outwash material:

Outwash plains are nearly level to gently sloping surfaces created in front of areas where glaciers stood stationary for considerable lengths of time. The deposits contain clean, stratified sands and gravels carried from the ice by running melt water. They tend to be a reliable source of glacial aggregates since they are usually well-sorted and the deposits have considerable aerial extent. Many large areas of central Minnesota are considered outwash plains; such as the Anoka sand plain and the areas around Wadena and Detroit Lakes.

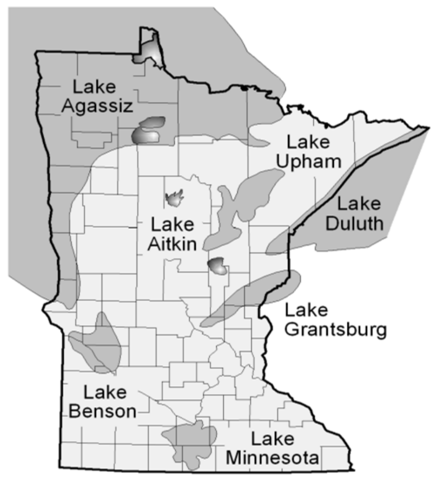
Eskers and tunnel valleys are narrow, sinuous ridges of stratified sands and gravel formed by subglacial streams. These ridges often extend tens of miles. Coarser sands and gravels were deposited with crude bedding, and finer materials were carried beyond the front of the glacier and deposited in lower energy lakes or streams. Eskers were deposited at the base of the ice and as the ice melted, it was only partially buried. Tunnel Valleys were formed as subglacial streams cut into the underlying soils and then deposited sorted materials. These materials have been totally buried by subsequent deposits of glacial drift. Because of their coarse-grained nature and length, both deposit types may provide an excellent source of granular materials.

Beach and delta deposits are generally fair to good aggregate sources. Beach and delta deposits mark the location of an ancient lake shoreline and river mouth, respectively. Wind-driven waves created the beach ridges or strand lines at the edges of many of the glacial lakes. These old beaches remain visible in many places in the northwestern portion of the state, and mark former shorelines, often elevated above the present topography of lake sediments. Lake Agassiz beaches are visible as linear ridges, averaging 10 to 15 feet (3 to 5 meters) in height, 400 feet (120 meters) or more in width, and extending up to tens of miles. These beach deposits consist primarily of sand and/or gravel, with characteristic cross bedding. They are excellent sources of granular materials and are favored road and building sites. Highway 11 between Karlstad and Roseau is built primarily on the Campbell Beach line of Lake Agassiz.

Kames are formed when a cavity in the glacial ice fills with soil and rock debris, the glacier melts, and this collection of material is left behind as a mound or irregularly shaped hill of crudely stratified sand and gravel.

Glacial lakes were formed as the great ice sheets melted and generated vast quantities of sediment-rich melt water. Several glacial lakes were formed in areas where the drainage was either blocked or inadequate to handle the sheer quantities of water generated. The largest of these lakes, **Lake Agassiz**, at one time occupied much of the northwestern part of the state. Deep-water lake clays and ancient sandy shoreline deposits indicate that, during several stages, Glacial Lake Agassiz stretched roughly from Browns Valley to central Manitoba, and from east of International Falls to just east of Devils Lake, ND. Lakes Winnipeg and Manitoba, Upper and Lower Red Lakes, and Lake of the Woods are all remnant lakes left over from the once-enormous Lake Agassiz. Other significant glacial lakes in existence during this period included Lake Duluth (proto-Lake Superior), Lake Minnesota, Lake Aitkin, Lake Upham, Lake Benson, and Lake Grantsburg (Figure 10-9). Glacial lake deposits typically occur as a vast flat plain of well-bedded silt and clay-rich sediment with occasional fine pebbles and boulders (dropstones) interspersed. These deposits are not good aggregate sources. Lake Agassiz clays are as thick as 150 feet (45 meters) along the northwestern border of Minnesota. Most lake sediments pose problems in highway construction because they are often unstable in the backslopes, have poor drainage, lack strength, and are frost susceptible.

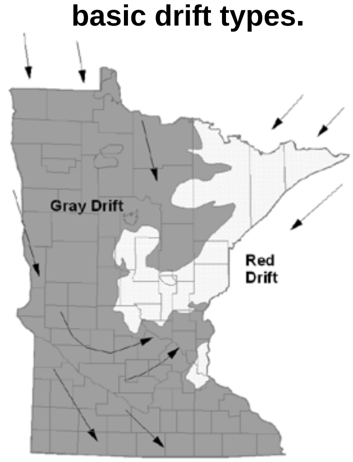
Figure A-9: Major glacial Lakes during Wisconsin Age



Red and Gray Drift

Glacial deposits of Minnesota can be divided into two basic drift types based on the general color of the deposit and the material it contains; **red drift** and **gray drift**. The red drift is typically sandy and contains rock fragments from the Precambrian bedrock (basalt, gabbro, and red sandstone) around the Lake Superior area and gets its reddish color from the high iron content of the material. The gray drift is silty, calcareous and contains abundant carbonate rock fragments from the Paleozoic sedimentary rocks in the Winnipeg area. The red drift is associated with the Superior and Rainy lobes and is found at the surface exclusively in eastern parts of the state.

Figure A-10: Red-Gray Drift Map representing the surface expression of the two basic drift types.

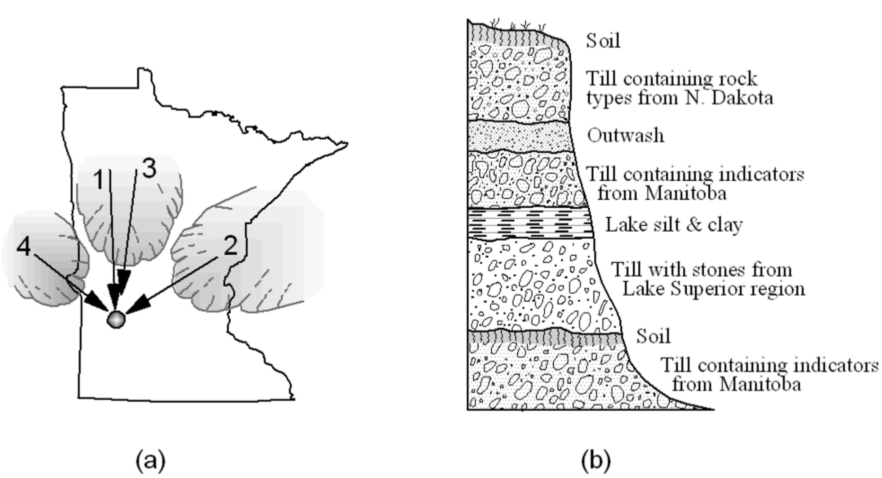


The gray drift is associated with the Wadena and Des Moines lobes. The Des Moines lobe, because of its more westward origin tracking across eastern North Dakota, carried with it fragments of a hard, gray to greenish-gray shale, plucked from the Cretaceous Pierre Shale of North Dakota.

The distinction between these drifts is important in terms of construction materials. The red drift sand and gravel is primarily igneous with minor amounts of sandstone making it a more durable aggregate. The gray drift has a high percentage of less durable carbonate particles, and in some areas has considerable amounts of shale, which is undesirable for most pavement and base applications.

Figure A-11 (a) shows a location in southwestern Minnesota where successive glacial advances produced a layered stratigraphy that has been used to reconstruct the glacial history of the area. At the bottom of the exposed section, Figure A-11 (b), is till from the Manitoba area (advance No. 1), followed by soil development, which indicates a time with no glacial activity. The second till indicates that the westward advance of ice from northeastern Minnesota (advance No. 2) reached this location. With the melting back of this lobe, a glacial lake was formed, contributing fine-grained sediments for the lake deposit. A second advance of ice from the north again deposited till from the Manitoba area (advance No. 3). As the ice melted, glacial streams deposited a well-sorted layer of outwash above the till. And finally, an ice lobe from the northwest covered the area (advance No. 4), and deposited till from North Dakota.

Figure A-11: Composite section of soil in southwestern Minnesota. (After Matsch, 1976)



The majority of Minnesota experienced periodic overriding by coalescing glacial ice lobes. However, one sliver of southeastern most Minnesota has historically been thought to have totally escaped modification by glacial ice. This region is known as the "**Driftless Area**", and includes the majority of Houston, Fillmore, Winona, Olmstead, Wabasha, and Goodhue counties. More recent work suggests that this area actually was overridden by ice during early glaciations; however, the drift deposits from that early event have been subsequently eroded or severely weathered, making identification difficult. Scattered patches of highly eroded old drift and occasional erratics have been reported in the driftless area, supporting this more recent conclusion.

While not extensively modified by ice, the driftless area has experienced enhanced topographic development as a result of glacial melt waters and modern rivers and streams. Surface materials in this area consist predominantly of loess-covered residual soils on bedrock, as well as colluvium and bedrock outcrops.

Post-glacial (Recent) Deposits

Such features are the result of reworking/deposition of soil materials, which have taken place since the last glaciation, hence - recent. A short discussion of these soil types and their general characteristics and uses follows.

Wind-Blown Deposits

Loess is a powdery, well-sorted, angular silt and fine sand, which was deposited during the last glaciation. Often just underlying the loess is a lag deposit of wind-faceted stones called **ventifacts**. While most common in southwestern and southeastern Minnesota, loess deposits are found in other portions of the state, occasionally between till layers. Loess deposits may stand at a near vertical angle with few stability problems. However, they are subject to rapid erosion by water or wind in the absence of a vegetative cover. Loess may also be subject to settlement problems; and bearing capacity may be affected in the presence of water, due to the collapse of the soil structure.

Both ancient and modern sand **dunes** can be identified in Minnesota. They are recognized by clean, well-sorted, frosted, sand-sized grains and cross bedding.

Alluvial and Lacustrine Deposits

Alluvium is material deposited by water, whether modern rivers and streams or glacial melt waters. Glacial alluvial deposits have been discussed in the previous section. Post-glacial rivers and streams continued the work of the glaciers, further eroding and entrenching the topography of Minnesota. The courses of the Mississippi, Minnesota, Red, and St. Croix Rivers are marked by deposits of sands and gravels, and silts and clays, which lie within the flood plains of these modern rivers.

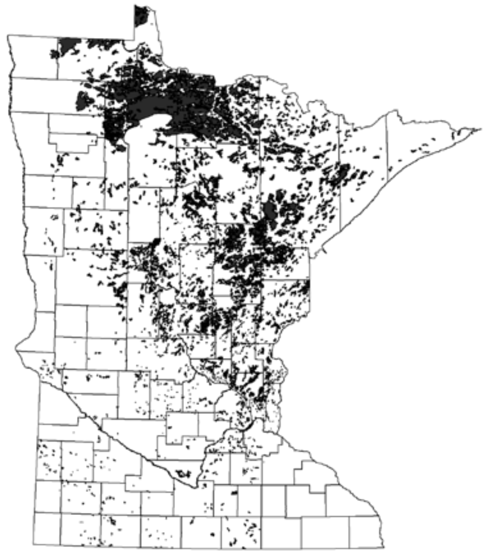
Terraces are remnants of former river flood plains, which occur as benched elevations above the present-day flood plain. They may contain sands and gravels or finer grained materials, or they may be marked by scoured surfaces on exposed bedrock. The high degree of maturity of Minnesota's major rivers means that their paths are not straight, but very sinuous. These rivers curve back and forth over their flood plains, cutting and reworking alluvial sediments in broad tight curves known as **meanders**. Occasionally, these meanders become so tight that they are breached in times of high water, cutting off a curve in the river and producing an **abandoned meander**. These abandoned sections of the river gradually become more distanced from the main river course, forming curved **oxbow lakes** that gradually fill inward with sediment and organic materials.

Lacustrine Deposits are fine-grained sediments deposited in fresh water lakes, which may or may not still be in existence. Wave action in lakes carries the finer grained silt and clay sized particles in suspension towards deeper water. As the water calms, these particles settle out and accumulate in the lakebed to form what is known as lacustrine soil. (As mentioned earlier, many lacustrine types of sediment were formed in glacial lakes.) Old lake plains are frequently evidenced by a very flat topography.

Peat is an organic deposits associated with lakes and wetlands. Peat is formed when organic material is deposited/forms in a predominantly cool oxygen-deficient environment. These conditions lead to preservation of the plant matter, with leaf and stem materials often remaining identifiable. **Peat bogs** are dominated by sphagnum moss with stands of black spruce and tamarack, and contain highly acidic waters. **Fens** are dominated by grasses, sedges, and reeds, with waters rich in minerals and less acidic than that of bog waters. These organic sediments typically form as vegetation encroaches into and then totally fills shallow lakes.

Minnesota is one of the "richest" states in terms of peat deposits (Figure 10-12). Peat is found extensively in north-central Minnesota, in the counties of Roseau, Lake of the Woods, and Koochiching, as well as Aitkin and southwestern St. Louis. In terms of soil description (see Chapter 4 for detailed description), peat is applied to soils with greater than 25% organic content. Other soils with less organic content fall between “slightly organic” at 2% organic material and “highly organic” beginning at 11% organic material (by weight), and also contain clays, silts and/or fine sands. Organic materials are obviously ill suited for road construction, due to their poor drainage, high potential for settlement, and variable organic and mineral content.

Figure A-12: Distribution of major peat deposits in Minnesota (from Geomorphology of Minnesota Database, 1997, U of Minnesota-Duluth; MGS; DNR, modified by Sharkey).



Weathering and Erosional products

In the vast periods of time when new rock weren't being formed by deposition or mountain building events, the existing bedrock was subject to continual attacks by weathering processes (such as wind, water and ice). These processes were mainly constrained to the near surface, but in areas where the bedrock had well developed joints, weathering could occur at substantial depth. In some areas, the weathering processes reduced strong, competent bedrock into clayey materials described as **residual soils**. In other areas, acidic groundwater circulated through jointed carbonate rocks producing voids and caves in what is referred to as **karstic terrain**.

Residual Soil

Residual soil consists of unconsolidated material that has weathered in place from the existing rock on which it lies. Depending on the degree of weathering, the product may contain stronger fragments of the parent rock, or it may be totally reduced to soil. The residual products of the weathering of Precambrian igneous and metamorphic rocks are common in southwestern and east-central Minnesota. The principal products of this in-place weathering are clay minerals, such as kaolinite and chlorite. The weathered material is generally dense (high Standard Penetration Test blow counts - up to 50/0.3 feet), and often contains remnants of the preexisting rock structure. Exposures of these weathering remnants are mainly confined to the Minnesota River valley west of Mankato, and in the St. Cloud area, and can be as thick as 100 feet (30 meters). The clays are often brightly colored, with hues of green, red, brown, and white. Care should be taken when working with residual soils because their properties as highly variable.

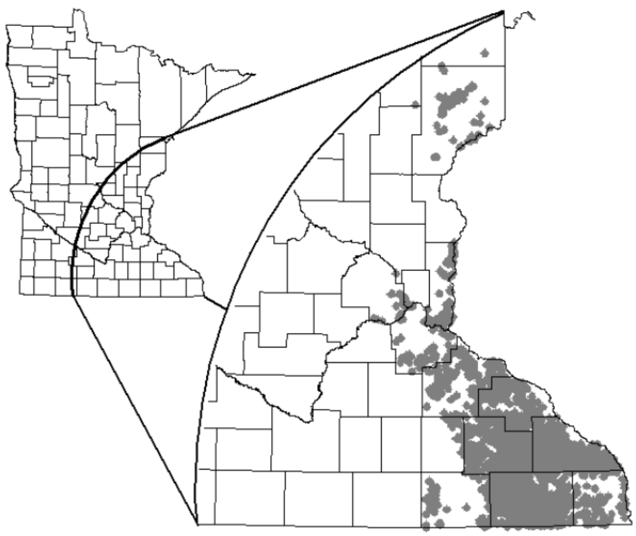
A residuum was also developed on the Ordovician carbonate rocks in Goodhue, Wabasha, Fillmore, Olmsted, and Mower Counties in southeastern Minnesota. The ferruginous clays of this deposit make up the Iron Hill Member of the Cretaceous Windrow Formation. These clays are typically gray to white but often contain brightly colored layers of reds and yellows associated with limonite deposition. In Fillmore, Olmsted, and Mower Counties, the weathering products contained concentrated iron ore (primarily goethite with minor amounts of hematite), which was commercially mined between 1942 and 1968.

Karst

Karstic landscapes can develop where limestone and dolostone are at or near the surface. Over long periods of time, the carbonate minerals in these rocks are dissolved by rain and ground water, creating enlarged joints, cavities, and caves. Karstic landscapes are usually characterized by features such as sinkholes, caves and disappearing streams. Much of the southeastern Minnesota landscape is checkered with sinkholes, surface depressions caused by the collapse of a cavern's bedrock roof and overlying soil (Figure 10-13). The abundance of sinkholes and other karstic features in this area of the state also coincides with the incised topography of the "driftless area" mentioned above. Most sinkholes in southeastern Minnesota are found in the Galena Group limestone and Prairie du Chien dolostone; which formed topographic 'ridges' or terrace-like 'steps', adjacent to river valleys, during the recent lull in glacial activity. The carving of river valleys through these and other sedimentary rocks ultimately deepened static water levels within the bedrock allowing greater travel distances of surface water to underlying aquifers and, thus, more effective dissolution of near-surface limestone and dolostone formations. In eastern Mower and western Fillmore Counties karst features are formed in limestone and dolostone of the Spillville and Maquoketa/Dubuque formations. Though karst features typically form in areas underlain by carbonates, sinkholes in Pine County are formed in glacial soils as a result of sediments being 'sucked' into dissolved or eroded cracks found in the underlying Hinckley Sandstone.

Sinkholes and other karstic features become problematic and hazardous when they develop in the vicinity of or under man-made structures such as roadways. The most commonly used solution when this occurs is to simply fill in the void with gravel or fill material. In most cases, this method provides merely a temporary solution since with time the fill material eventually is reclaimed by the void and the depression reappears. Long-term solutions employ methods that help control drainage into the void, such as constructing a clay liner over and around the void, or seal off the void completely, such as pressure grouting the cavity. Another method would include excavating the sinkhole and constructing a reinforced concrete 'patch' at the opening of the cavity to provide stability and prevent drainage into the void. Long-term solutions, however, should be based on thorough investigations which define the dimension of the collapse system, including the flow path and any subsidiary flow paths, and source of subsurface drainage. Drilling, excavation and geophysical methods, such as resistivity, reflection seismology, or ground penetrating radar are common means of providing this information. Despite the vast array of forensic tools available, the investigator is often left not entirely knowing the full subsurface extent of the void system as well as how it fits into the large scale karst system.

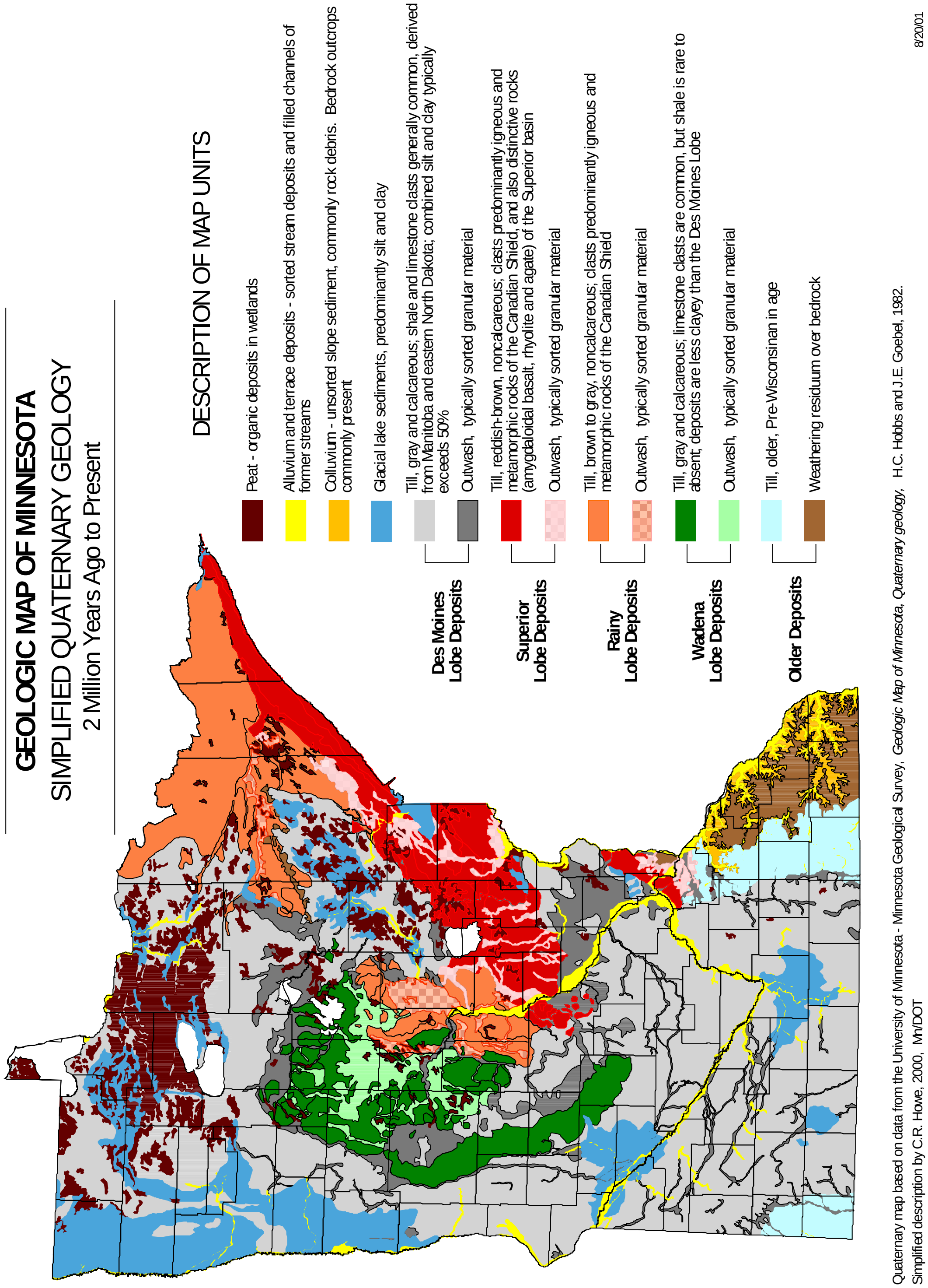
Figure A-13: Locations of active sinkholes in Eastern Minnesota (Map from MGS/DNR Sinkhole database, modified by Sharkey and Howe, 2003)



Colluvium

Colluvium is loose, unsorted, rock fragments and soil materials produced by gravity or mass wasting. Landslides, mudslides, and talus are all colluvial deposits. These heterogeneous deposits are generally identifiable in the field and typically lie in a slump at the base of a hill or rock outcrop. The presence of such material usually indicates an unstable area subject to debris flow, slides, slumps, or down-slope creep. Highly variable soil conditions should be expected, and additional soil borings may be appropriate. Variable subsurface conditions or possible boulders may give misleading information as to soil type and depth to bedrock. The presence of colluvial material suggests an area of possible slope instability and should be identified to prevent or control additional movement during or after construction.

Figure A-14: Shows the distribution of various Pleistocene and Holocene (Quaternary) deposits across the state of Minnesota.



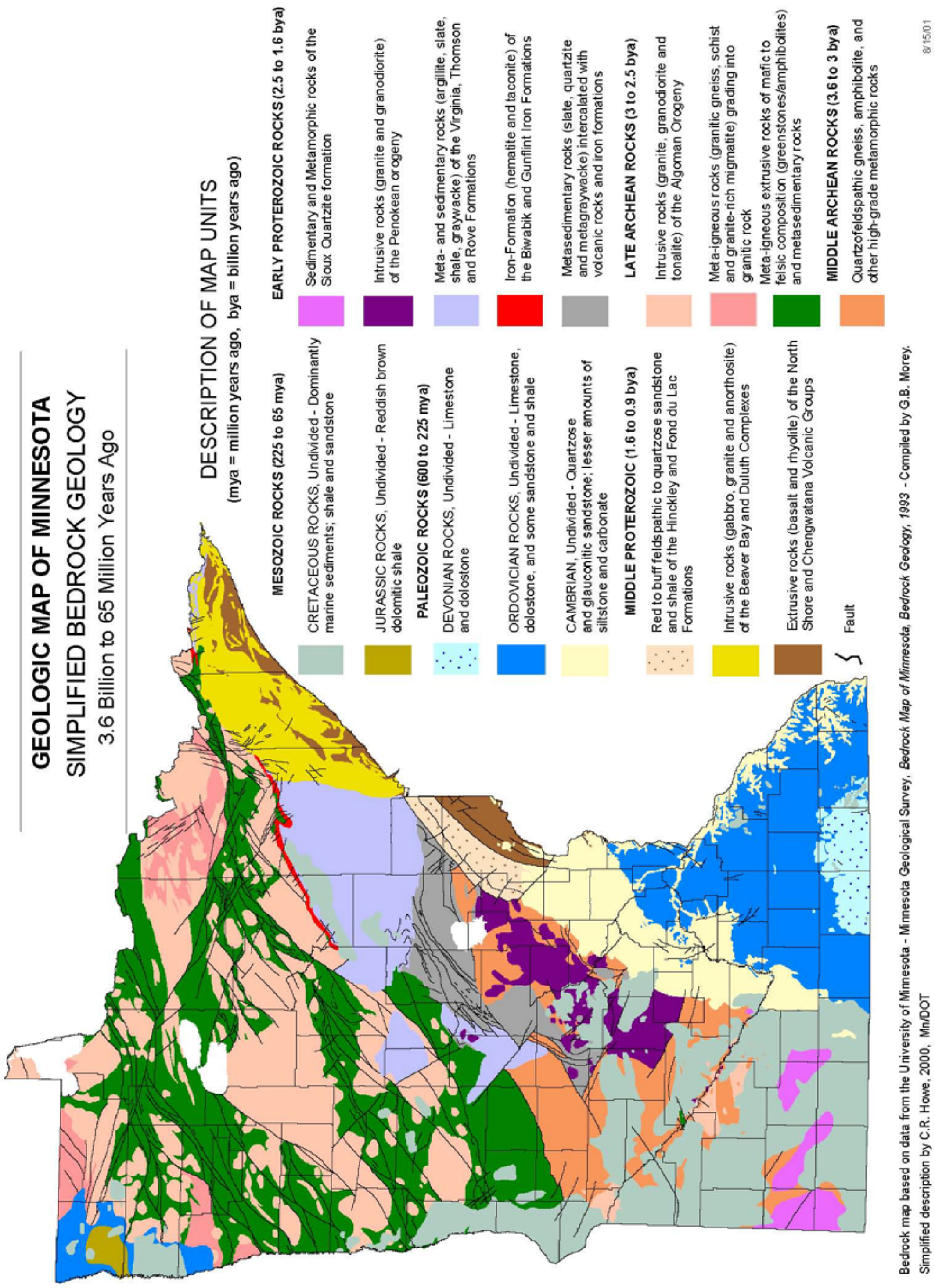


Figure A-15: Simplified Bedrock Geology of Minnesota

Figure A-16: Generalized Stratigraphic Column of Minnesota (taken from RI-65 Paleozoic Stratigraphic Nomenclature for Minnesota, Minnesota Geological Survey, page 84)

SOUTHEAST MINNESOTA

Chronostratigraphic units				Lithostratigraphic units		
Eon	Era	System	Series	Group	Formation	Member or bed
PHANEROZOIC	Paleozoic	Devonian	Upper	Cedar Valley Group	Lithograph City Formation (50)	Idelwild Member (25-30)
						Osage Springs Member (25-30)
			Middle		Coralville Formation (60)	Iowa City (35-40)
						Gizzard Creek (15-20)
					Little Cedar Formation (110)	Hinkle & Eagle Center Members (35)
						Chickasaw Shale (43)
						Bassett Member (70)
				Wapsipinicon Group	Pinicon Ridge Formation (47)	Davenport Member (13)
						Spring Grove Member (7)
						Kenwood Member (13)
					Spillville Formation (84)	Lake Meyer (15-20)
		Ordovician	Upper		Maquoketa Formation (85)	Clermont Member (20+)
						Elgin Member (62)
				Galena Group (345)	Dubuque Formation	
					Stewartville Formation (85)	Rifle Hill Member (38)
						Sinsinawa Member (32)
					Prosser Formation (62)	
					Cummingsville Formation (75)	
					Decorah Shale (80)	
						Carimona Member (11)
					Platteville Formation (30)	McGregor Member (22)
						Pecatonica Member (7, SE)
					Glenwood Formation (18)	
			?		St. Peter Sandstone (190, N)	Tonti Member (100-120, NE)
			Middle			Pigs Eye Member (40-65, NE)
			Lower	Prairie du Chien Group (320)	Shakopee Formation (240, SC)	Willow River Member (240, SC)
						New Richmond Member (55-60, SE)
					Oneota Dolomite (180-210, SE)	Hager City Member (180, SE)
						Blue Earth beds (4+)
						Kasota beds
						Coon Valley Member (60-85)
		Cambrian	Upper		Jordan Sandstone (110, NE)	Quartzose sandstone
						Feldspathic sandstone
					St. Lawrence Formation (130, SC)	Siltstone
						Dolostone
				Tunnel City Group (Franconia Formation) (190, NE)	Lone Rock Formation (175, SE)	Mazomanie Formation (115, NE)
						Reno Member (110, S)
						Tomah Member (23)
					Davis Formation (20, SW)	Birkmose Member (50)
					SW Wonewoc Sandstone NE (Ironton and Galesville Sandstones) (130, SE)	Very fine- to very coarse-grained sandstone
						Fine- to coarse-grained, cross-stratified sandstone
						Conglomerate
					SW Eau Claire Formation (250, SW) NE	Mixed sandstone and shale (22)
						Shale & siltstone (25)
						Greensand (96)
					Bonneterre Formation	Mixed sandstone and shale (98)
						Dolostone (80, SW)
						Red shale (75)
					SW Mt. Simon Sandstone (375, SE) NE	Upper (110+, NC)
						Middle (200+, SE)
						Lower (163, SW)
PROTEROZOIC	Middle				Hinckley Sandstone (<50, S to 500, N)	
					Fond du Lac Formation (8,000+)	
					Solor Church Formation (12,000-13,000)	
Undifferentiated					Older igneous and metamorphic rocks	

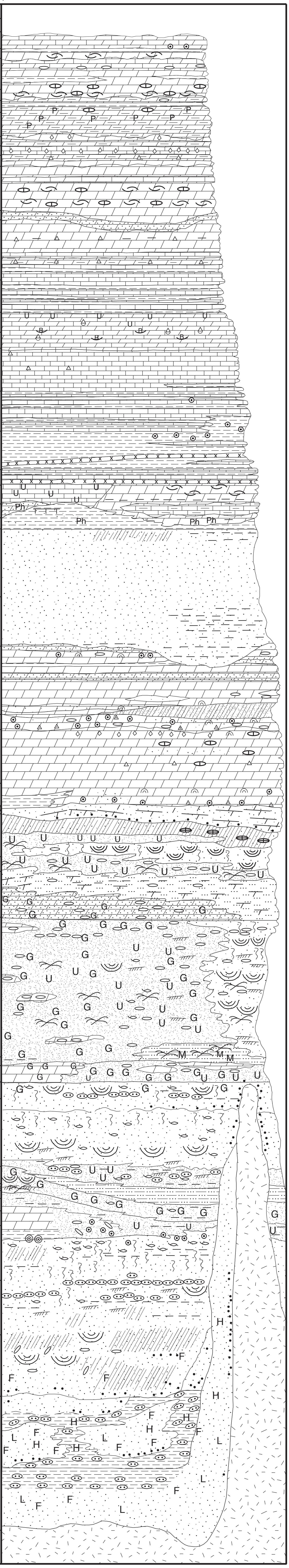


Figure A-17: Stratigraphic Succession of Precambrian Rocks of Minnesota (Adapted from "Geology of Minnesota: A Centennial Volume", 1972)

Era	Group	Formation	Event	Intrusive Rocks
Paleozoic		*Unconformity*		
600 m.y.		Hinckley Sandstone		
		Fond du Lac Sandstone	Keweenawan igneous activity (1000-1200 m.y.)	Duluth Gabbro complex and smaller intrusions along the North Shore
		Unconformity		
	North Shore Volcanic Group	Undivided, flows, tuffs, and sediments		
		Puckwunge Conglomerate		
Proterozoic		*Unconformity*		
		Sioux Quartzite		
		Unconformity		
		Rabbit Lake, Virginia, Rove, Thomson	Penokean orogeny (1600-1850 m.y.)	Granite in east-central Minnesota; small intrusions in Minnesota River Valley
	Animikie Group	Trommald, Biwabik,Gunflint		
		Mahnomen,Pokegama, Kakabeka		Vermilion and Giants Range granitic complexes; granite and gneiss (in part), Minnesota River Valley
2500 m.y.		*Unconformity*	Algoman orogeny (2400-2750 m.y.)	
	Knife Lake Group	Undivided slate, graywacke, conglomerate, tuffs, lavas		
Archean		*Unconformity*		
	Keewatin Group	Soudan Iron-formation	Laurentian orogeny	Granite at Saganaga Lake
		Ely Greenstone		
	Coutchiching	Metasedimentary rocks		
	Older rocks		3300-3550 m.y.	Gneiss (in part) Minnesota River Valley

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