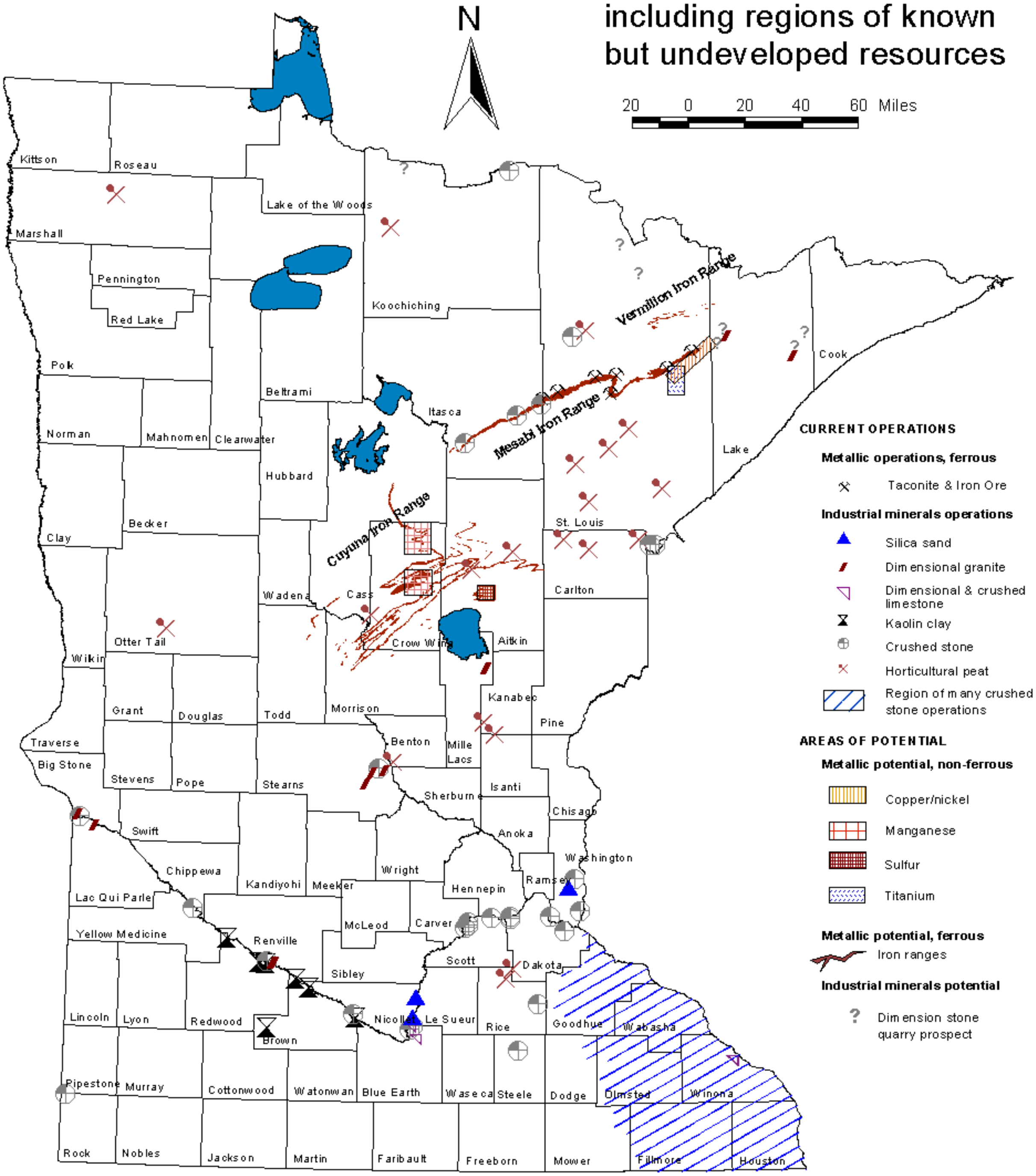
Mineral Industries of Minnesota

including regions of known but undeveloped resources



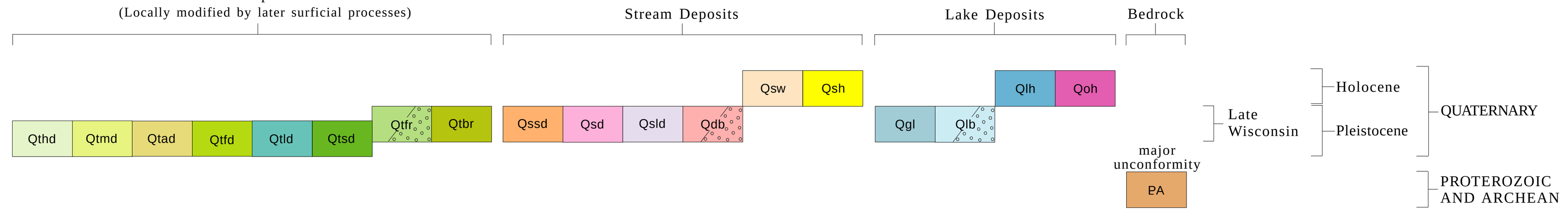
SURFICIAL GEOLOGY

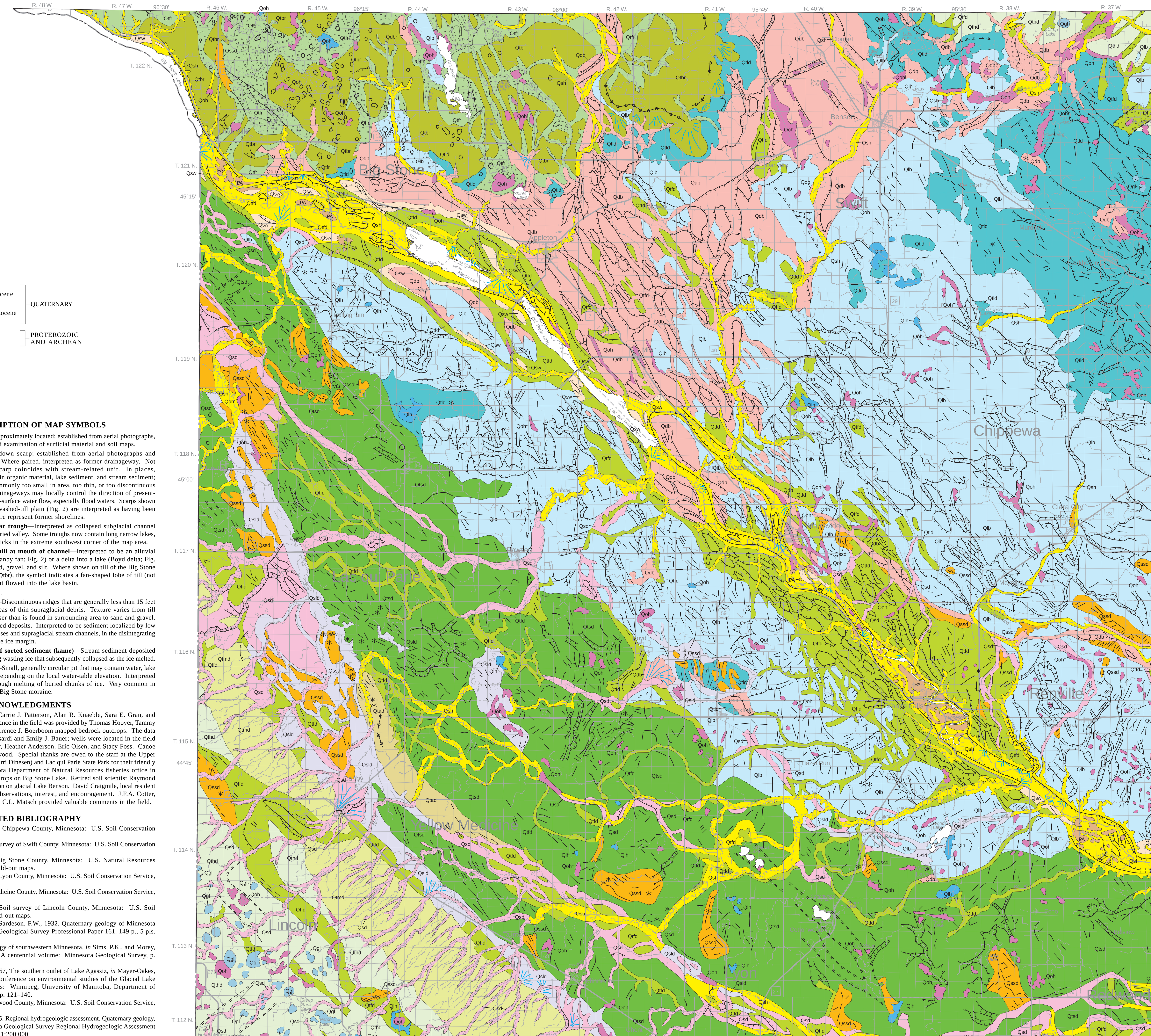
By

Carrie J. Patterson, Alan R. Knaeble, Sara E. Gran, and Stephanie J. Phippen

1999

CORRELATION OF MAP UNITS





Digital base modified from 1990 Census TIGER/Line Files of U.S. Bureau of the Census (source scale 1:100,000); county border files modified from Minnesota Department of Transportation files; digital base annotation by Minnesota Geological Survey

Universal Transverse Mercator Projection, grid zone 15
1927 North American Datum

SCALE 1:200 000

GIS compilation and cartography by
Joyce Meints and Philip Heywood

DESCRIPTION OF MAP UNITS

HOLOCENE AND LATE PLEISTOCENE

Qoh **Organic deposits**—Peat and sediment deposited in marshes and shallow lakes. Typically found in depressions interpreted to have formed through melting of buried glacial ice and along former glacial stream channels. Some deposits have been drained.

Qlh **Lake sediment**—Clay, silt, marl, and some organic material. The basins are commonly shallow (less than 10 feet deep), and the sediment may be thin; some basins have been drained.

Qsh **Stream sediment**—Stratified layers of silt, clay, and sand; some organic material. The sediment is coarser in the Minnesota River channel. Commonly located along glacial stream channels, where it may bury and incorporate coarser glacial stream sediment. The unit is not shown in narrow channels, although it is present to some extent wherever a modern stream flows. The unit includes the steep side slopes of channels, especially along the Minnesota River, where very little stream sediment is preserved. Rather, older units are exposed in bluffs, and colluvial sediment covers less steep slopes.

Qsw **Stream sediment of Glacial River Warren**—Stratified sand and gravel; commonly forms bars that protrude above Holocene stream sediment (map unit Qsh) in the River Warren gorge (Fig. 2). The unit is predominantly found where the river reworked existing deposits of sand and gravel. Glacial River Warren was mostly an erosive stream and created erosional (strath) terraces that have boulder lags at the surface.

PLEISTOCENE

DEPOSITS OF THE BIG STONE PHASE OF THE RED RIVER LOBE
(LATE WISCONSIN)

Qtbr **Till of the Big Stone moraine**—Till that contains lenses of sorted sediment and blocks of incorporated clayey lake sediment. Till texture and lithology are highly variable. Texture of the till matrix is loam to clay; yellow-brown where oxidized, gray where unoxidized. Clast rock types include carbonate, crystalline rock, shale (from none to 50 percent of the coarse sand fraction), and some lignite.

The unit is a complex of tills that were deposited along ice fronts that advanced into glacial Lake Benson (Figs. 1b and 2). The first advance to this position was probably of the Des Moines lobe, but the later advances were of the Red River lobe. Although the Red River lobe followed a path similar to that of the Des Moines lobe, its clast content and pattern of retreat indicate it originated in a different part of the ice sheet (directly north rather than north–northwest of the study area; Figs. 1a and 1b). The unit includes areas where lobate bodies of till, interpreted as flow tills, extend from the position of the former ice front (along the Big Stone moraine) into glacial Lake Benson (shown on map by fan symbol). Arcuate ridge crests mark the eastern extent of the moraine (crest line of moraine symbol; see Description of Map Symbols); they may be small push moraines. Elsewhere, the moraine has an irregular, extremely pitted surface, and the till contains many boulders. Pits are interpreted to have formed by burial and subsequent melting of small blocks of ice, possibly lake ice. Boulders are interpreted to have been incorporated locally from nearby granite outcrops. Linear depressions trending south and southeast through the moraine are interpreted to represent collapsed drainageways that eroded through or beneath debris-laden ice.

Qtfr **Till with stream-modified surface**—Till modified by flowing water; fluvially eroded and streamlined in places. Till texture, lithology, and color are as above (till of the Big Stone moraine; map unit Qtbr). Locally overlain by thin lag of sand and gravel or covered by silt and clay. Channel scars are common; channels may localize organic deposits (map unit Qoh), lakes, and modern streams and flood waters. Stipple indicates areas that collapsed after stream modification, probably from meltout of buried ice; the resulting topography is irregular.

DEPOSITS OF THE ALTAMONT, MARSHALL, GARY, ANTELOPE
AND YOUNGER PHASES OF THE DES MOINES LOBE (LATE WISCONSIN)

Qlb **Lake sediment of glacial Lake Benson**—Silt, clay, and some fine sand; rhythmically laminated in places. Upper part of unit is commonly a massive silt. The thickest, most continuous lake sediment is found in the northeastern quadrant of the former lake, where the lake may have survived longer after the southern part of the basin was drained. A discontinuous distribution of lake sediment in lake margins, ice-supported inlets and outlets, and a lack of clear shoreline features indicate that the lake was confined by stagnant ice. Minor linear ridges and small channels in the basin are interpreted to have formed beneath stagnating ice. Stipple indicates areas of collapsed lake sediment, which is interpreted as originating from meltout of buried ice; the resulting topography is irregular.

Qdb **Delta sediment of glacial Lake Benson**—Sand, gravel, and silt deposited by streams entering glacial Lake Benson. The largest deltas formed at the mouths of the Pomme de Terre and Chippewa Rivers. Minor deltas are located (1) on the northeastern side of the basin where the East Branch Chippewa River entered it (Swift Falls delta; Fig. 2); (2) at a higher elevation south of the East Branch Chippewa River where some small streams entered during a higher stage of the lake (within the Kerkhoven washed-till plain; Fig. 2); and (3) where Tenmile Creek entered the southwest part of the basin (Boyd delta; Fig. 2). Stipple indicates collapsed delta sediment, areas where a delta apparently formed on a buried glacier and possibly on lake ice; the resulting topography is irregular.

Qtsd **Subglacial till**—Dense, homogeneous till of the Marshall, Antelope, and younger phases of the Des Moines lobe. Texture of till matrix is loam to clay loam. Clast rock types include carbonate, crystalline rock, shale (average proportion for Marshall phase, 20–30 percent, for Antelope phase, 30–50 percent), and some lignite. Till surface has low relief. Locally overlain by thin (about 10–20-feet thick), discontinuous, supraglacial and englacial sorted sediment and till that typically form linear ridges. The sediment is interpreted to have been localized by crevasses in stagnant ice.

Qtld **Till with lake-modified surface**—Till that has at its surface a discontinuous, silty, clayey cap or a coarser, near-shore sediment. Till of all phases of the Des Moines lobe and the Big Stone phase of the Red River lobe, and, possibly, older glacial sediment are affected. Till texture, color, and clast lithology are similar to surrounding unit. The till surface has low relief. Erosion may have removed fine sediment, leaving a lag of clasts at the surface. Shorelines are locally marked by very low escarpments, beach ridges, or deltas (sediment of map unit Qdb).

Qtfd **Till with stream-modified surface**—Till modified by flowing water; fluvially eroded and streamlined in places. Till of all phases of the Des Moines lobe and, locally, older glacial sediment are included in this unit. Matrix texture, color, and clast lithology are similar to the original till unit before erosion. Locally overlain by a thin lag of sand and gravel or covered with silt and clay. Channel scars are common. Channels may localize organic deposits (map unit Qoh), lakes, and modern streams and flood waters. After stream modification, channels may have collapsed from meltout of buried ice.

Qtad **Till of the Antelope moraine**—Till that forms a low, broad ridge. Matrix texture is loam to clay loam; yellow brown where oxidized, gray where unoxidized. Clast rock types include carbonate, crystalline rock, a moderate to large proportion of shale (30–50 percent), and some lignite. The Antelope-phase ice margin is otherwise indicated by deposits of ice-marginal and ice-supported streams (Antelope Hills and Big Tom hills ice-supported-stream ridges; map unit Qssd; see also Fig. 2).

Qtmd **Till modified by slope processes**—Till along the slope of the Coteau des Prairies (a glacial erosional scarp); modified by slope wash, mass movement, and ice-marginal streams. Matrix texture is loam to clay loam; yellow-brown where oxidized, gray where unoxidized. Clast rock types include carbonate, crystalline rock, a low to moderate proportion of shale (10–20 percent), and some lignite. In the map area, this part of the Coteau slope was exposed after the Gary phase of the Des Moines lobe, but older units, including pre–Late Wisconsin units, may be exposed locally.

Qthd **Hummocky till**—Till that has an irregular surface expression and contains discontinuous lenses of clay, silt, sand, and gravel. Clast rock types include carbonate, crystalline rock, a low to moderate proportion of shale (10–20 percent), and some lignite. Unit is interpreted to have been deposited during the Altamont and Gary phases of the Des Moines lobe on and beneath stagnant, wasting ice, and it may have been subject to repeated mass movement during deposition. Unit includes small areas of supraglacial lake and stream sediment. Much of the relief is inherited in the northeast corner of the map area: the till there buries an older moraine of an ice advance from the northeast, and the till texture reflects the more sandy till of the underlying Alexandria moraine (Alexandria highlands; Fig. 2).

Qsd **Stream sediment**—Sand and gravel deposited by meltwater issuing from stagnating or receding ice of the Altamont and younger phases of the Des Moines lobe. Includes sediment of contemporaneous nonglacial streams, as well as younger and finer glacial and postglacial stream sediment. Broadly arcuate streams delimit former ice-margin positions (Marshall phase, Antelope phase, and possibly younger phases).

Qssd **Stream sediment formerly supported by ice**—Ridges of sand and gravel deposited by streams; some glacial sediment was deposited by gravity flow into channels. Interpreted to have been deposited in channels that were walled, supported, or enclosed by ice (eskers in the broadest definition of the term). Melting of ice may have led to local disruption of bedding. A significant amount of unsorted, glacial sediment may overlie the sorted sediment. Areas of this unit too small to delineate at the map scale are indicated by a line symbol (minor linear ridges; see Description of Map Symbols).

Qsld **Stream sediment overlain by lake sediment**—Similar to stream sediment (map unit Qsd) but buried by thin layers (generally less than 10 feet thick) of clay, silt, fine sand, and organic deposits. Streams flowing down the Coteau des Prairies slope deposited fans (for example, Canby fan; Fig. 2) that blocked streams flowing southeast between the base of the slope and the ice margin. The unit is also present where glacial streams backed up owing to some other type of constriction.

Qgl **Sediment of ice-walled glacial lakes**—Lake sediment in a high topographic position. Deposited in pools in stagnant ice. Fine sediment (clay and silt) may be rhythmically bedded near former lake centers; minor amounts of sand and gravel are present along former lake rims. Unit commonly contains thick, till-like, debris-flow deposits. Forms flat-topped circular uplands within hummocky till terrain in the southwest and northeast corners of map area.

PROTEROZOIC AND ARCHEAN

PA **Gneiss and granite, undivided**—Archean quartzofeldspathic gneiss; granitoid intrusions and low-grade greenstone belts. Exposed mostly along the bottom of the Glacial River Warren channel (present-day Minnesota River Valley), where overlying glacial sediment and weathered rock (saprolith) have been eroded. Saprolith is still preserved in some protected locations. The smoothly undulating rock surface is interpreted to have formed through chemical weathering while the rock was buried by thick regolith. Glacial and fluvial erosion selectively stripped away the regolith but has made only the minor modifications to the rock surface of striae, crescentic fractures, polish, and potholes.

DESCRIPTION OF MAP SYMBOLS

Geologic contact—Approximately located; established from aerial photographs, geomorphology, and examination of surficial material and soil maps.

Scarp—Ticks point down scarp; established from aerial photographs and topographic maps. Where paired, interpreted as former drainageway. Not indicated where scarp coincides with stream-related unit. In places, drainageways contain organic material, lake sediment, and stream sediment; the deposits are commonly too small in area, too thin, or too discontinuous to map. Former drainageways may locally control the direction of present-day surface and near-surface water flow, especially flood waters. Scarps shown on the Kerkhoven washed-till plain (Fig. 2) are interpreted as having been lake cut and therefore represent former shorelines.

Deep, broad, irregular trough—Interpreted as collapsed subglacial channel (tunnel valley) or buried valley. Some troughs now contain long narrow lakes, such as Lake Hendricks in the extreme southwest corner of the map area.

Fan-shaped sloping hill at mouth of channel—Interpreted to be an alluvial fan (for example, Canby fan; Fig. 2) or a delta into a lake (Boyd delta; Fig. 2) composed of sand, gravel, and silt. Where shown on till of the Big Stone moraine (map unit Qtbr), the symbol indicates a fan-shaped lobe of till (not sorted sediment) that flowed into the lake basin.

Crest line of moraine.

Minor linear ridges—Discontinuous ridges that are generally less than 15 feet high. Visible in areas of thin supraglacial debris. Texture varies from till that is slightly coarser than is found in surrounding area to sand and gravel. Chaotic and collapsed deposits. Interpreted to be sediment localized by low areas, such as crevasses and supraglacial stream channels, in the disintegrating glacier and along the ice margin.

Steep-sided mound of sorted sediment (kame)—Stream sediment deposited on, beneath, or along wasting ice that subsequently collapsed as the ice melted.

Circular depression—Small, generally circular pit that may contain water, lake sediment, or peat, depending on the local water-table elevation. Interpreted to have formed through melting of buried chunks of ice. Very common in certain parts of the Big Stone moraine.

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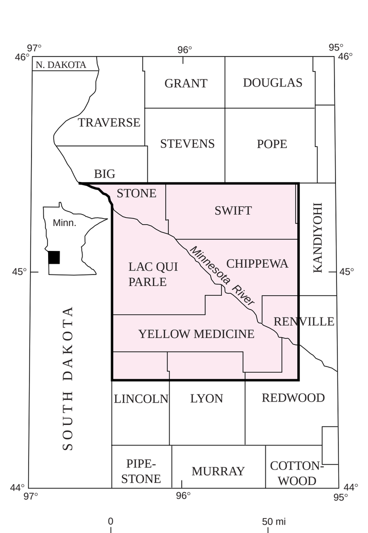
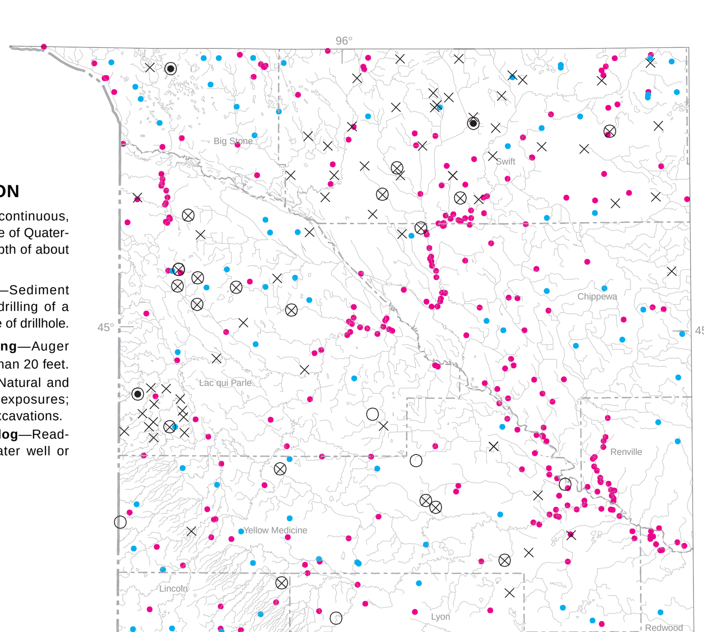
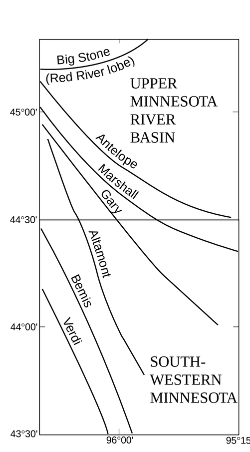


LOCATION OF MAP AREA



DISTRIBUTION OF THE PRINCIPAL SOURCES OF GEOLOGIC DATA
IN THE UPPER MINNESOTA RIVER BASIN



ICE MARGINS IN SOUTHWESTERN MINNESOTA

[The two areas represented are the regional hydrogeologic assessments for the upper Minnesota River basin (this map) and southwestern Minnesota (Setterholm, 1995). All the margins are of the Des Moines lobe, except the Big Stone margin of the Red River lobe.]

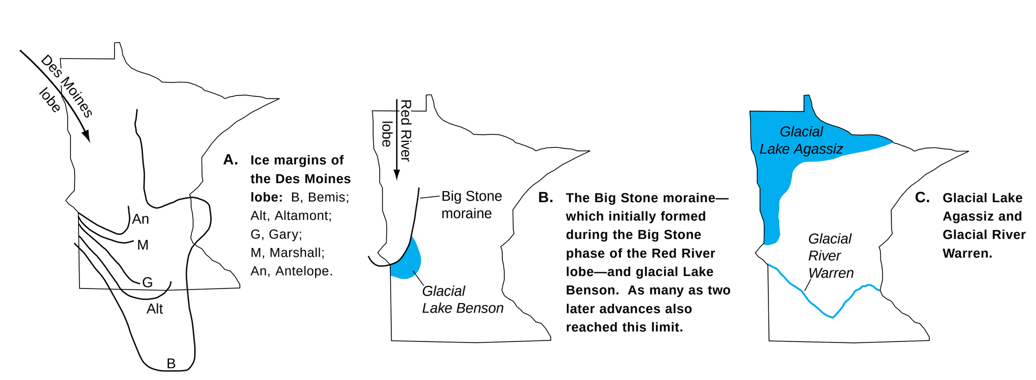
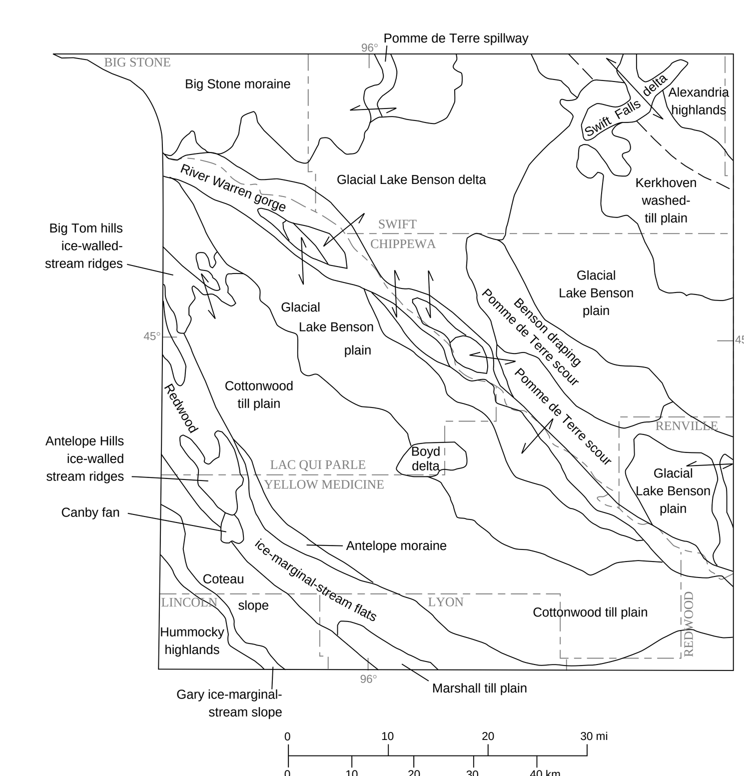


Figure 1. Sequence of glacial events in western Minnesota during the Late Wisconsin.

The Laurentide ice sheet was in steady decline as the Des Moines lobe was advancing, and each readvance was therefore less extensive than its predecessor (**A**). Ice margins of the phases may be marked by moraines, belts of hummocky topography, and ice-marginal-stream channels.

Glacial Lake Benson formed as the Des Moines lobe receded from the lowland now occupied by the Minnesota River (**B**). The Red River lobe advanced from the north to the position of the Big Stone moraine and into Lake Benson. The history of this lake, which was dammed by stagnant ice, is complex. The advance of the Red River lobe into the basin decreased the basin area and may have raised lake levels temporarily and (or) contributed to drainage. The scoured lake bottom indicates that the lake was overwhelmed by meltwater from the Pomme de Terre River, which may have been a spillway from another glacial lake north of the study area. The flow from the Pomme de Terre may ultimately have caused the drainage of glacial Lake Benson. (Lake Benson as shown in B is smaller than was its original area, which extended an unknown distance north.)

Lake Agassiz (**C**) formed when the Red River lobe receded north of the Big Stone moraine. This extremely large lake drained from its southern tip for much of its existence, creating the River Warren spillway, which followed the same general route as the drainage from glacial Lake Benson.



EXPLANATION

Alexandria highlands—High-relief morainic topography created by earlier ice advance of northeast-source lobe; overridden by Des Moines lobe with minor effect.

Hummocky highlands—Ice-stagnation topography. Thick, heterogeneous supraglacial deposits. Mostly map unit Qthd.

Coteau slope—Northeast-facing slope of Coteau des Prairies (glacial erosional scarp). Mostly map unit Qtmd.

Gary ice-marginal-stream slope—Stream-washed till and collapsed stream sediment along upper parts of Coteau des Prairies slope. The streams were confined by ice on northeast margins of channel (kame terrace). Mostly map units Qtfd and Qssd.

Marshall till plain—Flat-lying till plain of Marshall phase of the Des Moines lobe. Subglacial till (map unit Qtsd) is locally overlain by thin, patchy, supraglacial till.

Canby fan—Deposited at base of Coteau des Prairies by stream flowing downslope (shown by fan symbol on map unit Qsd). Such fans caused occasional ponding of southeast-flowing streams that ran parallel to Coteau base.

Redwood ice-marginal-stream flats—Formed by glacial streams flowing along margin of Des Moines lobe during Marshall and Antelope phases of the Des Moines lobe.

Big Tom hills ice-walled-stream ridges—Formed by ice-supported glacial streams flowing near ice margin during Marshall, Antelope, and possibly younger phases of Des Moines lobe. Streams may have been walled by ice, floored and walled by ice, or have flowed in ice tunnels.

Antelope Hills ice-walled-stream ridges—See Big Tom hills.

Antelope moraine—Short moraine segment marks Antelope phase of Des Moines lobe (map unit Qtad).

Cottonwood till plain—Flat-lying till plain of Antelope and younger phases of Des Moines lobe. Subglacial till (map unit Qtsd) locally overlain by thin, patchy, supraglacial till.

Glacial Lake Benson plain—Flat-lying lake plain created when meltwater from wasting Des Moines lobe, with contributions from various inlets, could not be drained efficiently through stagnant, debris-rich ice of Antelope-phase margin.

Glacial Lake Benson delta—Sediment deposited where streams, mainly the Pomme de Terre and Chippewa, entered glacial Lake Benson.

Boyd delta—Deposited where a glacial stream entered glacial Lake Benson. An older, ice-supported delta is offshore; a delta of yet another lake stage is present southward, near Clarkfield.

Pomme de Terre scour—Scour surface is traceable to mouth of Pomme de Terre spillway; large, erosive flow of water that created scour is also responsible for draining south part of glacial Lake Benson. Main scour-created channel probably obscured by current channel of Minnesota River. Secondary scour channel is now occupied by Chetamba Creek.

Pomme de Terre spillway—Uncommonly straight spillway that originated far north of map area (Pelican Rapids); main contributor to delta at north end of Lake Benson.

Benson draping Pomme de Terre scour—After the Pomme de Terre scour channel formed, the northern part of glacial Lake Benson basin refilled with water. It eventually drained south along channels now occupied by Sacred Heart Creek, Hawk Creek, and other southerly, subparallel streams.

Kerkhoven washed-till plain—Low-relief till surface that eroded during early high stage of glacial Lake Benson, probably while ice remained in basin. Concentration of deltas and linear features interpreted as shorelines mark stable lake level (indicated by a dashed line on figure).

Swift Falls delta—Sediment deposited where streams cutting through Alexandria highlands entered glacial Lake Benson from northeast.

Big Stone moraine—Hummocky moraine formed by Red River lobe as it advanced into glacial Lake Benson. Contains abundant small, circular pits, some arcuate moraine crests, and small lobes of flow till that protrude into area of lake.

River Warren gorge—Deep, straight trench created by drainage of the extremely large Glacial Lake Agassiz that formed behind Big Stone moraine.

Figure 2. Geomorphic regions of the upper Minnesota River basin. The regions in the explanation are ordered by age, beginning with the oldest. The symbol [symbol] indicates two areas of the same geomorphic type, one of which is unlabeled due to lack of space.

UNIVERSITY OF MINNESOTA
MINNESOTA GEOLOGICAL SURVEY
D.L. Southwick, Director

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QUATERNARY STRATIGRAPHY

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1999

INTRODUCTION

This plate provides an interpretation of the depositional setting, distribution and relative age of stratigraphic units documented from subsurface data and surficial mapping (Plate 1) in the upper Minnesota River basin area. The stratigraphic framework (Table 1) allows one to predict where certain units will be encountered, based on their known distribution and on the nature of the geologic processes that formed them. The stratigraphic framework facilitates exploration for targets such as subsurface aquifers. This plate includes a digital elevation model (Fig. 1), a map showing the thickness of glacial sediments (Fig. 2), and a model of the bedrock elevation (Fig. 3). Figure 4 shows the location of subsurface stream sediment associated with till units 5 and 6, and Figure 5 shows the location of subsurface stream sediment associated with Till units 7, 8, 9, and 10. The index map shows the location of the three cross sections (A–A', B–B', and C–C') and the three continuous cores (Figs. 6, 7, and 8). The essential characteristics of the 11 till units are given in Table 1, and the relative age of lake and stream sediments, and soil horizons or organic deposits is indicated.

Data used to develop the stratigraphic interpretation shown here include the three continuous cores that were drilled for this project (UMRB-1, 2 and 3, Figs. 6, 7, and 8), water-well records, cuttings from rotary drill holes, gamma logs of wells and holes drilled for scientific purposes, as well as shallow auger holes, and the multi-till outcrops present along tributaries to the Minnesota River (see figure on Plate 1 for data location). These data are of varying quality. Outcrops are the best source of information because the continuity and context of the units can be directly observed. A few outcrops such as those along the Yellow Medicine River and Hawk Creek near their confluence with the Minnesota River include many or most of the tills recognized. The continuous cores (Figs. 6, 7, and 8) provide deep (as much as 225 ft below the land surface) stratigraphic information away from the Minnesota River, although the nature of the contacts and the continuity of the units is not as easily discerned. Gamma logs are useful for identifying sandy units, some till-till contacts and the contact between glacial sediments and bedrock. Water-well records also assist in distinguishing sandy from non-sandy units, as well as in identifying coloration associated with oxidized zones (which may represent units formerly at the land surface), and allowing an interpretation of the depth to bedrock. Cuttings from rotary drilling provide information about the general lithology and approximate contacts of subsurface units, but mixing during the drilling process results in the cuttings becoming increasingly unreliable with depth.

Past glaciations had global effects, and one can use information from a variety of sources to interpret glacial events. Ocean sediments and ice cores provide evidence for numerous glacial periods during the Pleistocene Epoch. The Upper Midwest was directly affected by ice during at least three of the ten most recent glacial periods during the last 800,000 years (Table 1). During any glacial period, many ice lobes can flow into an area, and each lobe may have multiple advances. For example, surficial sediments together with the Quaternary stratigraphy show that during the last glaciation the upper Minnesota River basin was affected by the Red River lobe and the Des Moines lobe. These ice lobes did not simply advance and retreat. Quaternary sediments indicate that they show complex patterns including multiple advances, stagnations, and retreats. The oscillations of the Des Moines lobe alone indicate four distinct ice margins in the area—the Altamont, Gary, Marshall, and Antelope ice margins (Plate 1). There are probably three to five more ice margins between the Antelope ice margin and the Big Stone moraine in the north of the area mapped. The Des Moines lobe therefore had the potential to stack as many as seven to nine similar tills in the region of the Big Stone moraine, with the number decreasing to the south. A total of five Des Moines-lobe till units has been distinguished in this study. The Red River lobe as well as earlier ice lobes probably behaved in a similar manner.

Multiple advances of one ice lobe may create very similar tills. If the source area for the ice does not change from one glacial period to the next, the tills of these glacial periods will be similar, which adds to the difficulty of distinguishing between stratigraphic units. In the upper Minnesota River basin region most of the ice advanced from the north-northwest or north, incorporating many of the same rock types. Thus, out of the total of 11 till units identified in the region, only till unit 9 is from a distinctly different source area. Therefore an exposure of till examined out of stratigraphic context cannot be classified on the basis of field criteria alone. There is also significant overlap in the laboratory-determined criteria (textural and grain-count data, Figs. 6, 7, and 8). Many of the units documented from outcrops and even some from continuous cores have not been positively classified (they are identified as 'unnamed tills' in Table 1 and Figs. 6, 7, and 8). Geochemistry of the fine fraction of the till (Gowan, 1998) may help classification, but was not undertaken.

Quaternary glacial sediment in the study area is thickest in the southwest and northeast (Fig. 2). Geomorphic and subsurface data (see cross sections A–A' and B–B') provide some evidence for an unconformity (a gap in the geologic record) beneath till units 4, 5, and 6. This unconformity is associated with the broad lowland that extends from the northwest to the southeast through the region (Figs. 1 and 2). The unconformity may be the result of erosion related to advances of the Des Moines lobe. Erosion surfaces are difficult to identify from well-logs, and very few holes penetrate the deepest glacial sediment, but if this hypothesis is correct, till units directly beneath the Des Moines lobe tills in the lowland should correlate with more deeply buried till units in the highlands to the southwest and northeast. There may be some tills that are preserved in highland areas that are missing from the lowland areas.

We have not determined dates for any of the many advances of the Des Moines lobe in the upper Minnesota River basin region, but based on the continuity of the surficial deposits it is possible to correlate ice margins with dated margins in nearby areas (Table 1). Organic remains (red cedar branches) present beneath the Des Moines-lobe tills are older than 48,500 yrs B.P., and beyond the limits of radiocarbon dating. Evidence for previous nonglacial periods has been found above till unit 9 (a soil development horizon) and below till unit 10 (wood, peat and other organic material). These nonglacial deposits may contain distinct pollen and plant assemblages that would allow correlation with nonglacial deposits elsewhere in the region.

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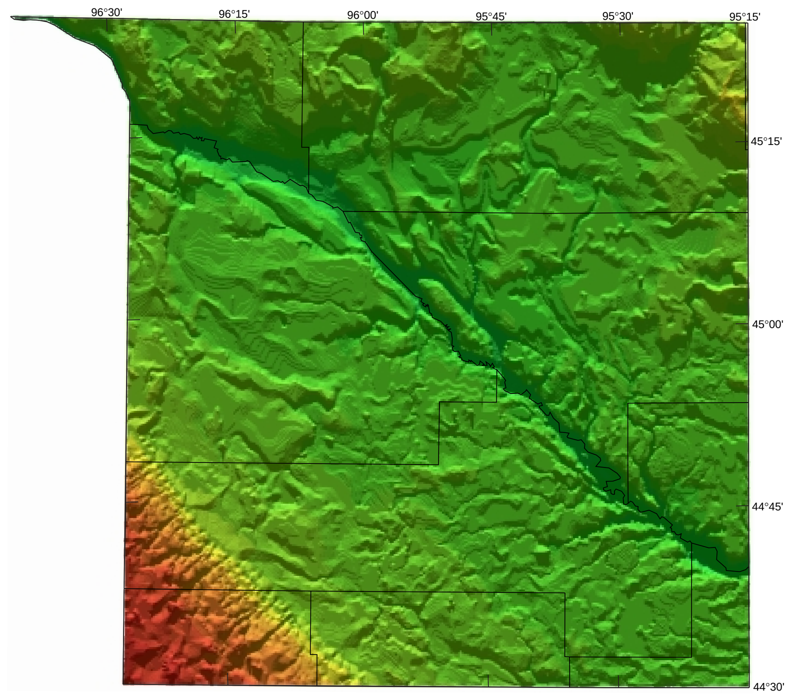


Figure 1. Digital elevation model of land surface. Shaded relief is portrayed using U.S. Geological Survey 90-meter grid cell digital elevation data. The model has 940 ft of overall relief, with a maximum grid elevation of 1790 ft in the southwest corner of the study area.

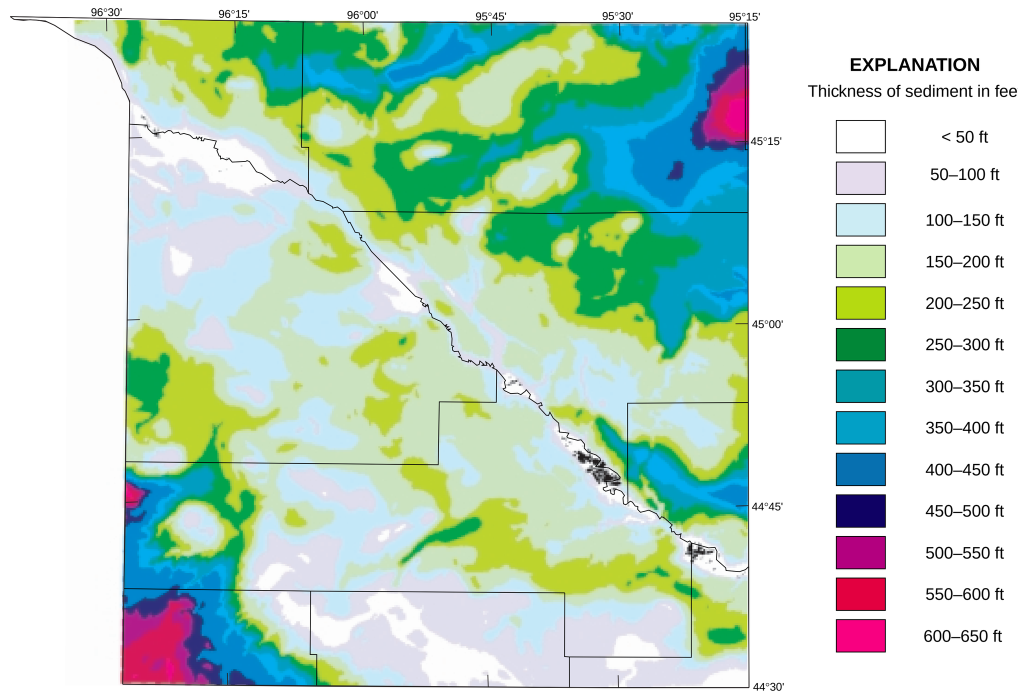


Figure 2. Thickness of Quaternary sediment. The sediment between the land surface and bedrock surface is mostly of glacial origin. Thickness was determined by subtracting the gridded bedrock-elevation data (Fig. 3) from the gridded land-surface digital elevation data (Fig. 1). The sediment thickness data were then contoured with a 50-ft interval. Bedrock outcrop is shown in black. Quaternary sediment is thinnest (<50 ft, white) in the upper Minnesota River Valley, which marks the axis of the most recent advances of the Des Moines lobe. Quaternary sediment is thick (600–650 ft) in the southwest where Des Moines-lobe deposits overlie a thick sequence of older, pre-Wisconsinan glacial sediment that forms the Coteau des Prairies. Quaternary sediment is also thick in the northeast were the Des Moines lobe deposits overlie sediments of the Alexandria Moraine.

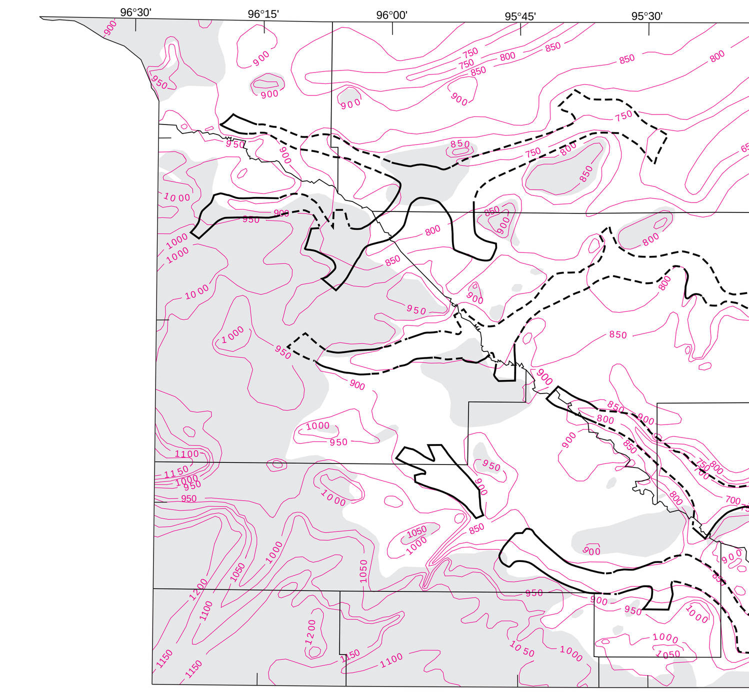


Figure 3. Bedrock elevation, extent of Cretaceous bedrock, and distribution of subsurface stream sediment greater than 20 ft thick at the base of the Quaternary units. Bedrock elevation is contoured in 50-ft intervals. The gray stipple shows the extent of Cretaceous bedrock. Stream deposits that are well constrained by existing data are indicated by solid lines. Stream deposits that are poorly constrained by existing data are indicated by dashed lines. The bedrock surface elevation model was created using data obtained from water-well construction, scientific test drilling and bedrock outcrops. Bedrock mainly crops out along the Minnesota River Valley. The bedrock elevation data were interpreted and a geomorphologically probable surface was contoured. The model exhibits 665 ft of overall relief, with a maximum elevation of 1285 ft and a minimum elevation of 620 ft. In areas to the southwest the uppermost bedrock is Cretaceous in age. Elsewhere, Cretaceous-age rock was either not deposited or was eroded prior to or during the Quaternary, and the first bedrock encountered is Precambrian in age. These areas of Precambrian rock may be deeply weathered (weathering took place prior to the late Cretaceous) so that saprolite (deeply weathered rock) is encountered at the elevations indicated here, and unweathered rock is only found at greater depths below the bedrock surface. The bedrock surface contoured here was not necessarily ever completely exposed at the land surface. The dendritic network of stream sediments documented in areas of lower elevation (shown with heavy solid and dashed lines) indicate that at least the central corridor (about two-thirds of the mapped area) was exposed at the surface.

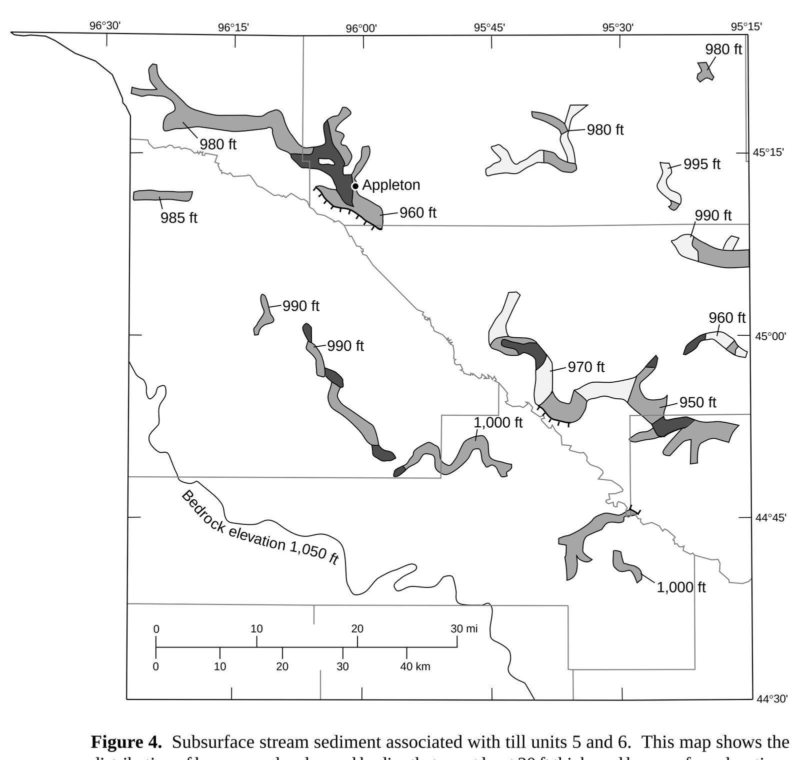


Figure 4. Subsurface stream sediment associated with till units 5 and 6. This map shows the distribution of known sand and gravel bodies that are at least 20 ft thick, and have surface elevations between 950 ft and 1000 ft. Elevations given on the map are the approximate upper surfaces of the sediment, although this will vary along the stream course. The medium gray areas indicate sand and gravel bodies that are well defined by existing data. The light gray areas indicate sand and gravel bodies defined by fewer data points. Areas where sand and gravel deposits may be connected to the underlying sand and gravel units (Fig. 5) are shown in dark gray; in these areas water in otherwise-separate aquifers may be hydraulically connected. Areas along the Minnesota River Valley where buried aquifers may be hydraulically connected with surface waters are shown with a hachured line. The 1,050 ft bedrock elevation contour is shown. The subsurface sand and gravel deposits were identified using well-construction records. The stratigraphic context of these deposits was used to construct probable channel networks. In the region near Appleton, sandy subsurface stream sediment is abundant, and these aquifers are probably hydraulically connected to the bedrock surface.

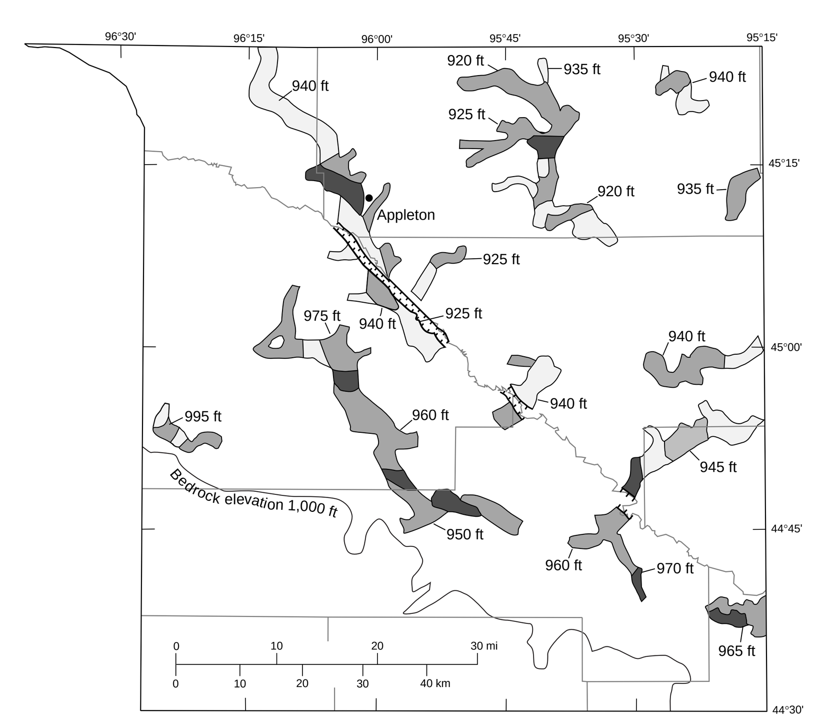
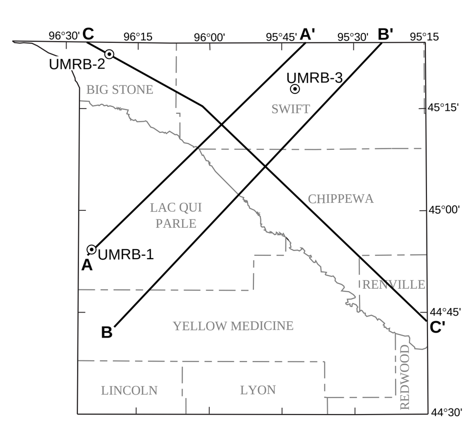


Figure 5. Subsurface stream sediment associated with till units 7, 8, 9, and 10. This map shows the distribution of sand and gravel bodies that are at least 20 ft thick, that have upper surface elevations mostly between 975 ft and 920 ft (stream sediments at higher elevations are shown in Figure 4). The medium gray areas indicate sand and gravel bodies that are well defined by the existing data. The light gray areas indicate sand and gravel bodies defined by fewer data points. Areas where stream sediments may be hydraulically connected to otherwise separate underlying sands (Fig. 3) are shown in dark gray. Areas where the buried aquifers associated with till units 7, 8, 9, and 10 may be hydraulically connected with surface waters along the Minnesota River valley are indicated with a hachured line. The sand and gravel body with a surface elevation of 995 ft is stratigraphically linked to subsurface stream sediments associated with till units 7, 8, 9, and 10. The elevations given on the map are the approximate upper surfaces of the sand and gravel bodies, although this may vary along the stream course. The subsurface sand and gravel deposits were identified using well-construction records. The stratigraphic context of these deposits was used to construct probable channel networks.



INDEX MAP
Shows location of cross sections and drill core.

CROSS SECTIONS

The location of cross sections A–A', B–B', C–C', and of the continuous drill core are shown on the index map. The well-log data has mostly been projected in to the lines of cross section. The well-logs used are from wells drilled within one mile of each cross-section line. Where the vertical lines representing well-log data terminate above or below the ground surface elevation on the cross sections, data is derived from a nearby location where the ground surface elevation varies from that on the line of cross section. For most logs it is only possible to tell sandy units from non-sandy units. The cross sections are drawn at map scale (1:200,000) with 50 times vertical exaggeration. It is not possible to show units less than 20 ft thick. Some units are shown as being thicker than they actually are, some are grouped with others, and others are simply not shown. Many units that appear on the surficial map (Plate 1) were too thin to show on the cross sections. Units Qsh, Qsd, Qsld, Qsw, Qtld, Qtbr and Qssd are shown on the cross sections as undifferentiated Quaternary surficial sediments, with their identity indicated. Sediments of glacial Lake Benson are identified as separate units (sandy delta sediment; silts and clays), as are other lake sediments. Till units 1, 2, and 3 (numbers refer to unit designation in Table 1) are grouped on the cross sections, as are till units 5 and 6, till units 7 and 8, and till units 10 and 11. There are also an uncertain number of undifferentiated units below till unit 11 that are grouped with till units 10 and 11.

In some cases the till units were grouped, not because they were too thin to show, but because it was impossible to tell them apart with the data available. A dashed line through these grouped units indicates the possible location of a contact based on the presence of sand layers at that horizon. Unit 9 is thin and apparently discontinuous but is not grouped with any other unit because it is the only till of northeastern source. Its reddish brown color is occasionally noted in well logs and it is easily distinguished in outcrop. However, it can be gray when unoxidized, and may include both local and northwest-provenance clasts. It can be missed if special attention is not paid to pebble types. Subsurface sand and gravel bodies have not been assigned to till units, they are shown as separate units on the cross sections. Clayey or silty lake sediment in the subsurface is mostly too thin or too difficult to portray on the cross sections. Lake sediment from a once-extensive lake lies stratigraphically below till units 7/8, and is exposed in valleys of the Yellow Medicine River and Hawk Creek. In some places till unit 7 is stratified, indicating that the ice depositing it advanced into a lake.

Table 1. General description of major stratigraphic units

	Sedimentary Unit	Texture	Composition, Grain-Count Data	Location, Correlation, Ice-lobe affiliation	Possible Age
Till units grouped on cross sections	Till unit 1	Clay 21–25%; sand = silt	Trace or no Cretaceous shale; Precambrian ≤ Paleozoic	Present in Big Stone moraine	10,000–30,000 yrs B.P. Late Wisconsinan (marine oxygen isotope stage 4)
	Till unit 2	Clay 22–29%; sand ≤ silt	Cretaceous shale 15–30%; Precambrian = Paleozoic	Present in Big Stone moraine; may correlate to St. Hilaire Fm. (Harris and others, 1995); a till of the Red River lobe	
	Lake sediment	Laminated, varved or massive silts and clays		Glacial Lake Benson II	
	Till unit 3	Clay 25–40%; sand < silt	Cretaceous shale 30–60%; Precambrian = Paleozoic	Present in the Big Stone moraine may correlate with Dahlen Formation (Harris and others, 1995); a Des Moines-lobe till	
	Lake sediment	Laminated, varved or massive silts and clays		Glacial Lake Benson I	
	Till unit 4	Clay 20–35%; sand < silt	Cretaceous shale 30–60%; Precambrian ≥ Paleozoic	Present in the Cottonwood Till Plain; main surface unit in study area; a Des Moines-lobe till	
Till units grouped on cross sections	Till unit 5	Clay 20–30%; sand = silt	Cretaceous shale 20–30%; Precambrian ≥ Paleozoic	Present in the Marshall Till Plain; may be missing due to erosion; a Des Moines-lobe till	
	Till unit 6	Clay 19–27%; sand < silt	Cretaceous shale 16–22%; Precambrian ≤ Paleozoic	May be missing due to erosion; probably includes older phases of the Des Moines lobe; may correlate with units D-1 through D-3 (Patterson and others, 1995)	
	soil development				
Till units grouped on cross sections	Till unit 7	Clay 15–24%; sand = silt	Cretaceous shale 0–10%; Precambrian > Paleozoic	Well exposed, locally stratified may correlate with Granite Falls Till of Matsch (1973)	120,000–200,000 OR 420,000–460,000 yrs B.P. (marine oxygen isotope stages 6 or 12)
	Till unit 8	Clay 18–25%; sand < silt	Cretaceous shale 0–15%; Precambrian ≤ Paleozoic	Not stratified; otherwise similar to Till unit 7; may correlate with SWRA-1 or SWRA-2 (Patterson and others, 1995)	
	Lake sediment	includes soil development and organic deposits > 48,500 yrs B.P.			
	Till unit 9	Clay 10–21%; sand > silt	Trace Cretaceous shale; Precambrian > 80% (5–25% red)	Superior provenance; correlates with Hawk Creek Till of Matsch (1973)	420,000–460,000 OR 620,000–660,000 yrs B.P. (marine oxygen isotope stages 12 or 16)
Till units grouped on cross sections	Till unit 10	Clay 20–30%; sand = silt	Cretaceous shale 0–10%; Precambrian > Paleozoic	Contains wood (red cedar)	
	organic deposits				
	Till unit 11	Clay 20–30%; sand ≤ silt	Cretaceous shale 0–15%; Precambrian ≤ Paleozoic	Not many samples	

A pavement of faceted and striated boulders is present at various stratigraphic horizons between till units 4 and 5, 4 and 6, 6 and 8, and 9 as well as between till units 5 and 7.

There are an uncertain number of unnamed till units present beneath till unit 11 at some locations

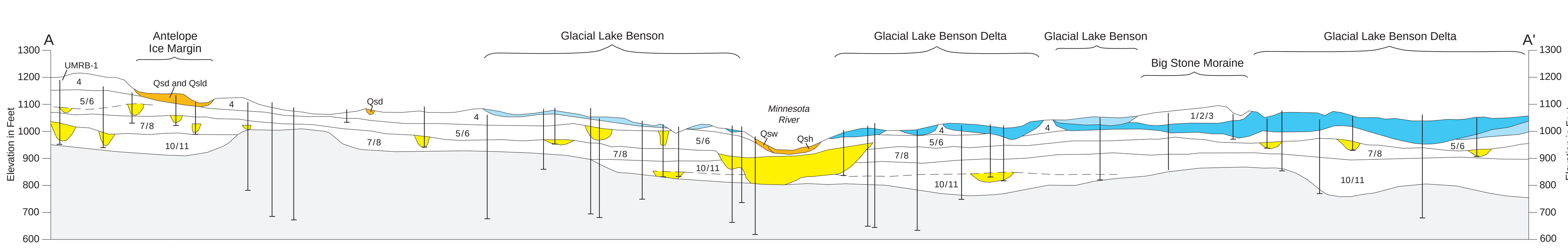
EXPLANATION FOR CROSS SECTIONS

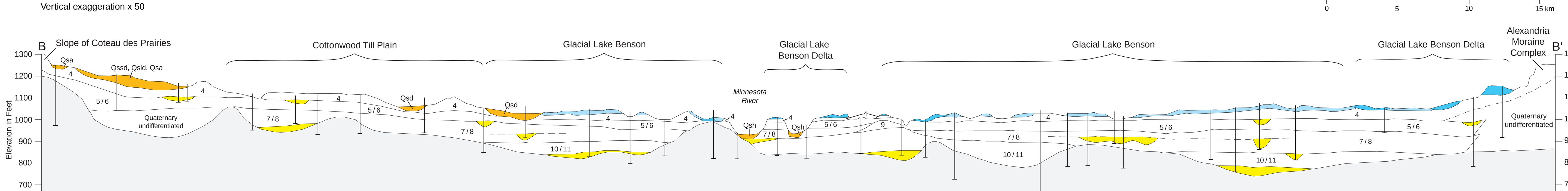
- Surficial stream sediments
- Sandy delta sediment of Glacial Lake Benson
- Silts and clays of Glacial Lake Benson
- 7/8 Till unit. Numbers indicate stratigraphic unit(s). Some till units are grouped.
- Subsurface sand and gravel units
- Lake sediment, clayey silt and very fine sand
- Bedrock, undifferentiated
- Drill hole
- Possible contact between till units

SCALE 1:200 000
0 5 10 mi
0 5 10 15 km

CONTINUOUS DRILL CORE

Three holes drilled for this study (Figures 6, 7, and 8) provide continuous, essentially undisturbed four-inch-diameter core to depths of 225 ft (UMRB-1 and UMRB-2) and 205 ft (UMRB-3). The core provides the most detailed and reliable source of information available on subsurface stratigraphy. Figures 6, 7, and 8 show the elevation above sea level and the depth below ground surface for each core. Matrix texture of the glacial sediment and other non-glacial sediments is presented here as cumulative percentages of sand, silt and clay for each interval sampled. Gravel percentages are not given. Natural gamma logs are useful for distinguishing sandy units (which plot to the left) from more clayey units (which plot to the right). The core descriptions are summaries of the stratigraphic units identified. A geologist monitored the drilling and logged the core on site. The core was then sampled and described in greater detail in the laboratory. The interpretation of the stratigraphic units is shown in italics, and a summary of the inferred stratigraphic sequence is shown in Table 1. The coarse sand grain (1–2 mm) composition was determined. Coarse sand grains were divided on the basis of the inferred age of the rock type (Precambrian, Paleozoic and Cretaceous) and counted. The resulting counts were then averaged for samples within each stratigraphic unit. The relative proportions of different rock types can indicate the source and path of the depositing ice, and assist in correlation of units over a wider area.





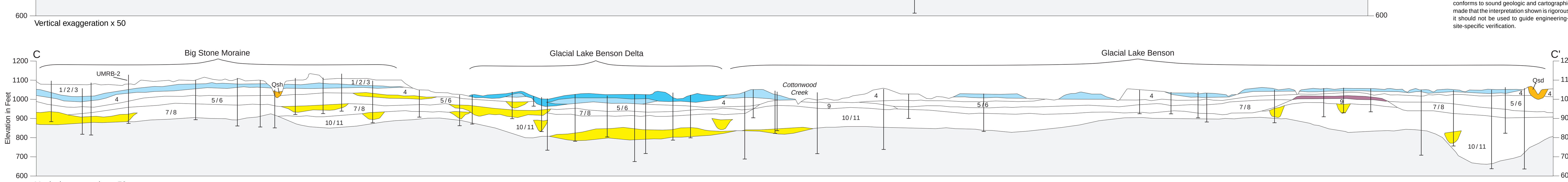
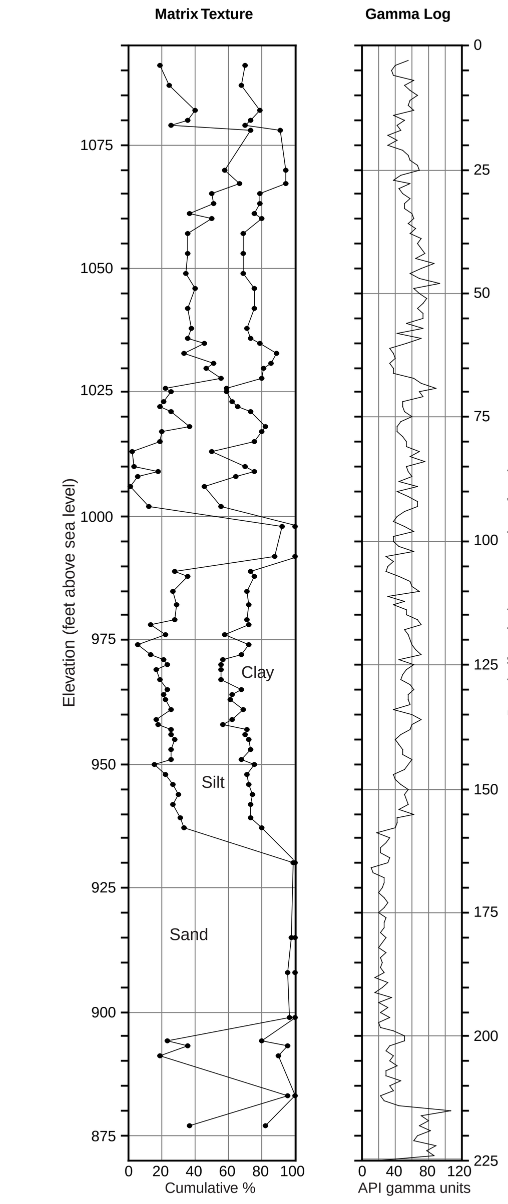
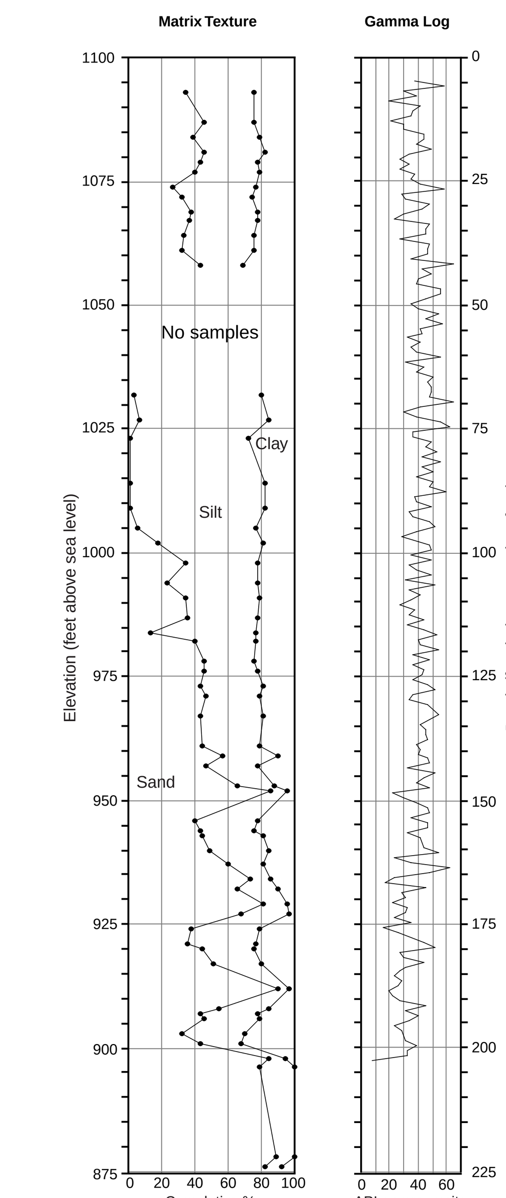


Figure 6. UMRB-1 (SW1/4 NW1/4 sec. 34, T. 117 N., R. 46 W., Lac qui Parle County)



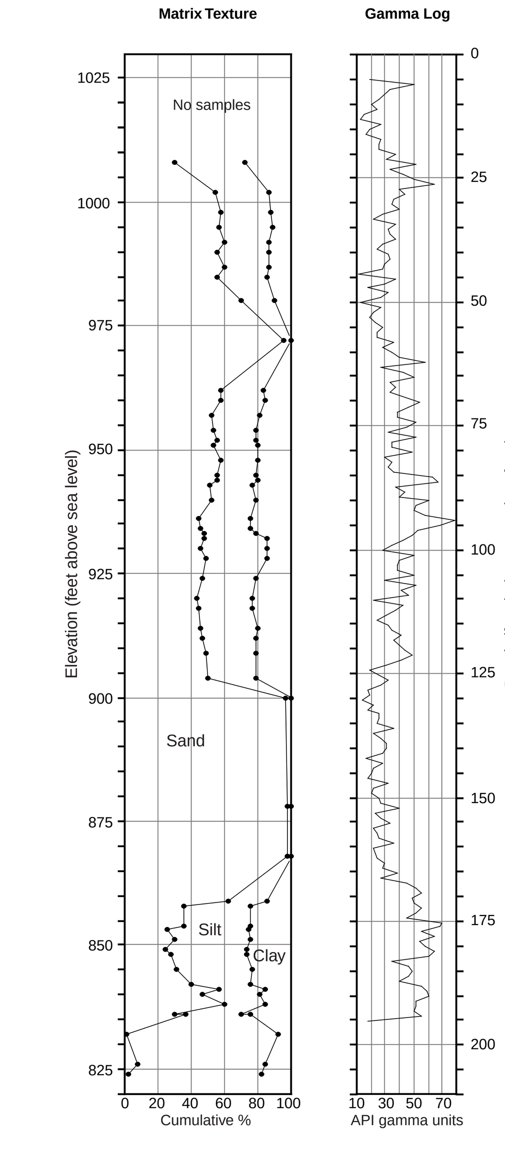
Lithologic Description and Interpretation	Coarse Sand Grain Counts Precambrian:Paleozoic:Cretaceous
0–9 ft Diamicton, light olive brown; upper 5 ft is clast-poor and has a silt matrix; secondary gypsum at 4–5 ft; below 5 ft the matrix is a clay loam. *Unnamed till*	55 : 29 : 16
9–18 ft Diamicton, loam matrix, variable to olive brown in color; sharp upper contact, although similar to overlying till; abundant shale clasts; sandy and gravelly towards base. *Till unit 4*	42 : 25 : 33
18–29 ft Sandy loam; gray; laminated in places. *Lake sediment*	
29–36 ft Diamicton, loam to sandy clay loam matrix, black; below 33 ft becomes denser, more uniform and fissile, with a clay loam to loam matrix; includes Cretaceous non-Pierre Shale clasts (probably Fairport Mbr. of Carlile Fm.). *Unnamed supraglacial or glaciolacustrine till*	42 : 27 : 31
36–61 ft Diamicton, clay loam matrix; dense and uniform; very dark gray to black; fissile in places; clasts include Cretaceous concretions and shells. *Unnamed till (not till unit 4)*	52 : 17 : 31
61–62.5 ft Medium sand grading up to fine sand; dark gray to dark gray brown. *Stream sediment*	
62.5–63.5 ft Fine sand and silt with scattered clasts; mottled. *Lake or stream sediment*; **63.5–68 ft** Diamicton, loam to sandy clay loam matrix; light olive gray. *Till unit 7*	85 : 12 : 03
68–72 ft Diamicton, clay to clay loam matrix, dark gray to black, contains waxy dark shale clasts; sharp contact with overlying unit; silt stringers present throughout; thin fine sand and silt layer near base; basal 1 inch is sheared. *Unnamed subglacial till*	62 : 23 : 15
72–75 ft Diamicton, silty clay loam to clay loam matrix; light gray to dark gray; calcareous. *Unnamed till*	98 : 02 : 00
75–93.5 ft Silt with clay and fine sand, coarsens upward; includes shells, and some pebbles; at 84.5 ft it is slightly coarser, more oxidized, and contains clay intraclasts in silt; at 92 ft the sediment grades down to a very clayey and dense unit. *Lake sediment*	
93.5–95 ft Diamicton, silty clay matrix; dark grayish brown; chalk clasts, large shale clasts, numerous Precambrian grains. *Unnamed till*	99 : 01 : 00
95–100 ft Coarse sand with pebbles; dark grayish brown to light olive brown; grus-like composition; contains no mafic, metasedimentary, sedimentary or carbonate grains. *Leached stream sediment*	98 : 02 : 00
100–105.5 ft Gravel; calcareous; basal contact is a sharp erosion surface. *Unleached stream sediment*	76 : 24 : 00
105.5–117.5 ft Diamicton, clay loam to loam matrix; gray brown to dark gray; calcareous; contains blocky shale clasts and yellow orange-stained carbonate clasts. *Till unit 8*	54 : 46 : 00
117.5–120.5 ft Diamicton, silty clay loam to clay matrix; olive brown; upper and lower contacts marked by thin black silty zone (possibly a soil or reworked fines); numerous lenticular white zones (marl); silty clay near lower contact. *Flow till or glaciolacustrine facies of till unit 8*	45 : 55 : 00
120.5–123.5 ft Silty clay loam; very dark gray; locally carbonate-rich. *Lake sediment*	
123.5–129 ft Diamicton, clay matrix with polished pebbles; olive brown; contains secondary carbonate on fractures; strongly oxidized. *Unnamed till*	60 : 32 : 08
129–158 ft Diamicton, clay loam matrix, with silty clay loam and silt loam; black to very dark grayish black; variably oxidized; calcareous throughout; snail shell and wood at 137.5 ft; lighter gray below 141.5 ft; shark tooth at 148.5 ft; sharp basal contact. *Unnamed till*	53 : 45 : 02
158–199 ft Fine to coarse sand; grayish brown; calcareous throughout; 80 percent quartz grains; scattered pebbles at 181 ft; at 186 ft it is a medium to coarse sand with local concentrations of black granules (lignite?); below 186 ft it is a coarse sand with polished and rounded pebbles. *Stream or delta sediment*	90 : 10 : 00
199–201 ft Diamicton, silt loam matrix; very dark gray. *Unnamed till*	61 : 38 : 01
201–204 ft Gravel, silt matrix, some matrix support; below 202 ft it is almost clast-supported. *Gravelly till or silty gravel sieve deposit*	44 : 51 : 05
204–218 ft Sand, fines upward from medium to coarse sand to fine sand with silt; gray; calcareous throughout. *Stream or delta sediment*	81 : 19 : 00
218–219 ft Diamicton, loam matrix; gray. *Unnamed till*	59 : 40 : 01
219–225 ft Shale; dark; waxy. *Cretaceous bedrock*	

Figure 7. UMRB-2 (NE1/4 NE1/4 sec. 18, T. 122 N., R. 46 W., Big Stone County)



Lithologic Description and Interpretation	Coarse Sand Grain Counts Precambrian:Paleozoic:Cretaceous
0–5 ft Pebbly silt; dark grayish brown; organic-rich; calcareous; weakly laminated. *Holocene lake sediment*; **5–25 ft** Diamicton, loam to clay loam matrix; soil structure in upper part; light yellowish brown to pale brown; non-calcareous to weakly calcareous; includes carbonate clasts, but no shale clasts. *Till unit 1*	46 : 54 : 00
25–45 ft Diamicton, loam matrix; similar to overlying till unit 1, but firmer; dark gray to light brownish gray. *Till unit 2*	39 : 41 : 20
45–96 ft No core recovered from 45–66 ft. Below 66 ft: silt loam with sand and occasional granule- and pebble-size clasts; finely laminated; increase in amount of pebbles and granules in lower 1.5 ft. *Glacial Lake Benson sediment*	
96–117 ft Diamicton, silt loam matrix, possible soil structure in upper part; dark gray; blocky; calcareous; below 100 ft the sediment is a dense, fairly uniform diamicton with a loam to silt loam matrix, and contains abundant shale granules and pebbles between 100 ft and basal contact. *Till unit 4*	22 : 18 : 60
117–130 ft Diamicton, loam matrix, contact with overlying unit may be gradational between 114 to 117 ft; thin sand layers; very dark gray; extremely dense; fewer shale clasts than in overlying unit. *Till unit 5*	39 : 35 : 26
130–132 ft Fine sand, fines upward; dark gray; sharp upper and basal contacts. *Lake sediment*; **132–135 ft** Diamicton, loam matrix; very dark gray; clasts include dolomite, granite and shale. *Till unit 5*	40 : 38 : 22
135–137 ft Cobbly gravel with coarse sand. *Stream sediment*; **137–141 ft** Diamicton, loamy matrix; very dark gray; clasts include dolomite, granite and shale. *Till unit 5*	35 : 37 : 28
141–142 ft Fine sand; light grayish brown; sharp upper and basal contacts. *Lake sediment*	
142–149 ft Diamicton, loam matrix; dark gray; calcareous; includes limestone, shale, metamorphic and igneous clasts, some are distinctly striated; becomes sandier towards base, where it is a sandy loam to loamy sand with visible sand layers. *Till unit 5*	41 : 38 : 21
149–153 ft Coarse sand with fine pebbles; gray; includes small lignite grains; thin diamicton at 152 ft; fine sand layer at 153 ft. *Delta or stream sediment*; **153–165 ft** Diamicton, loam matrix; very dark gray; uniform and unoxidized; gravelly and sandy at base. *Till unit 6*	38 : 39 : 23
165–175 ft Coarse sand and gravel, poorly sorted; sharp upper contact with overlying till unit 6; above 167 ft it is a clast-supported gravel with a sandy matrix that grades up to a sand and pebbly sand; below 167 ft it contains less fines in the matrix, but is still not well sorted. *Stream sediment*	39 : 39 : 22
175–184 ft Diamicton, loam matrix; very dark grayish brown; dense and firm; includes sand layers up to 1 inch thick; pebbly towards the base; Sharp basal and upper contacts. *Unnamed till*	41 : 34 : 25
184–193 ft Coarse sand with pebbles; variable color; better sorted near base. *Stream sediment*	58 : 38 : 11
193–196 ft Very pebbly diamicton, loam to clay loam matrix; dark gray; layers of coarse sand at 198 ft. *Till unit 8*	48 : 46 : 06
196–200 ft Coarse, poorly sorted sandy clay loam; pebbly diamicton layer with loam matrix at 198–199 ft; dark grayish brown. *Resedimented till?*	43 : 50 : 07
200–203 ft Sand; gray with black laminae; finely laminated; laminae include lignite (?) or other organic material. *Alluvium*; **203–207 ft** Coarse pebbly sand; sharp upper contact; contains well-rounded pebbles. *Stream sediment*; **207–223 ft** Sand; fines upwards from well-sorted coarse sand to medium-fine sand. *Stream sediment*; **223–225 ft** Loamy sand; dark grayish brown. *Stream or lake sediment*	63 : 32 : 05

Figure 8. UMRB-3 (NE1/4 SE1/4 sec. 8, T. 121 N., R. 40 W., Swift County)



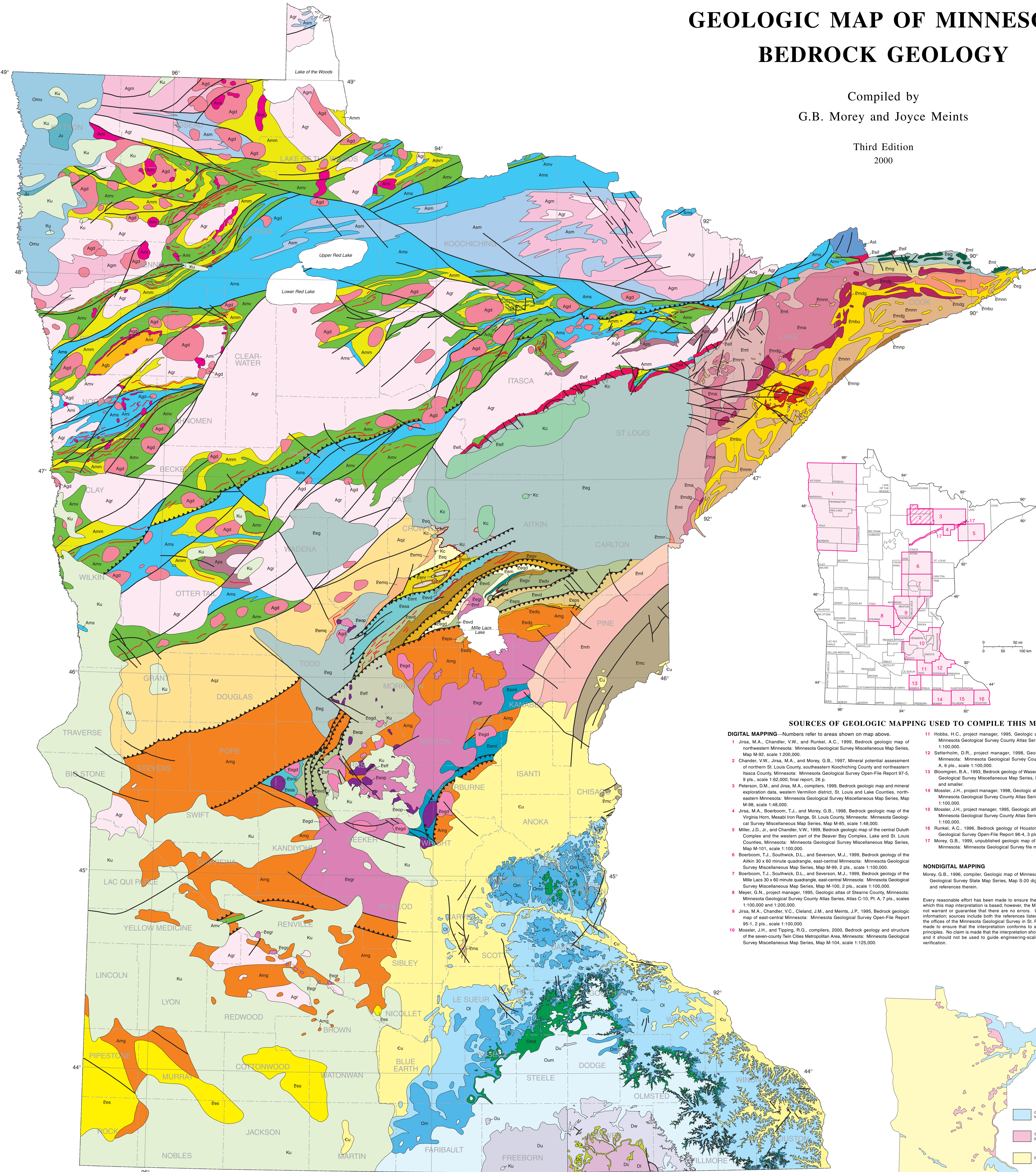
Lithologic Description and Interpretation	Coarse Sand Grain Counts Precambrian:Paleozoic:Cretaceous
0–4 ft Artificial fill	
4–5 ft Fine sand; gray and yellow brown. *Eolian sand or lake sediment*	
5–10 ft Organic-rich black sand grading down to dark gray sand then very fine sand (olive gray) with silt; slightly calcareous; sulfur smell. *Buried soil on delta sediment*	
10–22 ft Fine sand; black to dark gray; grades down to dark gray fine to medium sand; color change parallels grain-size change; calcareous; contains scattered pebbles. *Delta sediment*	
22–33 ft Diamicton, clay loam to sandy loam matrix; dark gray; very soft; contains abundant carbonate clasts and very few shale clasts. *Till unit 7*; **33–35 ft** Coarse sand with pebbles, fining up to fine sand; sharp upper contact; fine silty sand near base. *Delta or stream sediment*; **35–43 ft** Diamicton, sandy loam matrix; dark gray to very dark gray brown; includes sand at 40 ft and a gravel layer at 40.5 ft; firm below 40.5 ft. *Till unit 7*	62 : 29 : 09
43–47 ft Fine silty sand; pale gray; mostly quartz sand; contains lignite granules. *Delta and/or lake sediment*	
47–48 ft Sandy diamicton, sandy loam matrix; gray; sharp upper and lower contacts. *Resedimented till*	79 : 19 : 02
48–65 ft Medium to coarse pebbly sand; variable color; contains lignite granules and other black grains as well as red grains; grades down from a fine-to-coarse pebbly sand with minor silt as well as granules and pebbles, to a medium-to-coarse sand with granules to a coarse pebbly sand at base. *Stream sediment*	77 : 22 : 01
65–90 ft Diamicton, sandy loam matrix; dark gray; calcareous throughout; includes many sand layers between upper contact and 72 ft; includes Cretaceous pyrite and limestone clasts; high gamma signal below 83 ft probably due to blocky Cretaceous shale clasts. *Resedimented till*	70 : 20 : 10
90–95 ft Diamicton, clay loam matrix with cobbles near base; dark gray; similar to overlying unit (65–90 ft); includes speckled shale clasts; records the highest gamma signal. *Unnamed till*	56 : 21 : 23
95–125 ft Diamicton, loam matrix texture, blocky structure at top (probably a truncated soil profile); very dark gray-brown; contains dominantly Precambrian grains, some carbonate grains, and only rare Cretaceous grains; unoxidized (very dark gray-brown to very dark gray) below 99 ft; sandy at 111.5 ft and 112–113.5 ft; very firm till below 113.5 ft; sharp basal and upper contacts. *Unnamed till(s)*	76 : 23 : 01
125–145 ft Fine sand; variable color; contains lignite and wood grains and clay intraclasts; contact with overlying unit is sharp; below 129 ft it is a well sorted, fine to medium sand; at 137.5 ft it includes a zone with lignite, wood and organic material; at 143.5 ft there is a sharp change to very fine sand. *Stream sediment*	82 : 11 : 07
145–168 ft Medium to coarse pebbly sand, fining upwards; contains lignite, shell fragments, red sandstone, red shale, and red siltstone in pebble and coarse-sand fraction; at 155 ft it changes sharply to a quartz-rich upwards-fining very fine sand unit that contains red (northeast-source) grains near the base. *Stream sediment*	85 : 14 : 01
168–193 ft Diamicton, with matrix composed of alternating layers of dark reddish gray sandy loam and dark gray clay loam; includes a possible truncated soil profile; core missing from 171.5 to 173 ft; below 173 ft it is a dark gray to grayish brown diamicton with scattered red pebbles and seams of diamicton with a dark reddish gray sandy loam matrix. *Glaciotectonically layered till*	85 : 13 : 02
193–195 ft Clay; black; grades down to bedded silt, very fine sand then clay, with wood at the base. *Lake sediment*	
195–205 ft Very fine sand to silt; gray; rare pebbles; homogeneous, with occasional hints of bedding; includes shells and flakes of black organic material. *Lake sediment*	

REGIONAL HYDROGEOLOGIC ASSESSMENT
QUATERNARY GEOLOGY — UPPER MINNESOTA RIVER BASIN, MINNESOTA

GEOLOGIC MAP OF MINNESOTA
BEDROCK GEOLOGY

Compiled by
G.B. Morey and Joyce Meints

Third Edition
2000

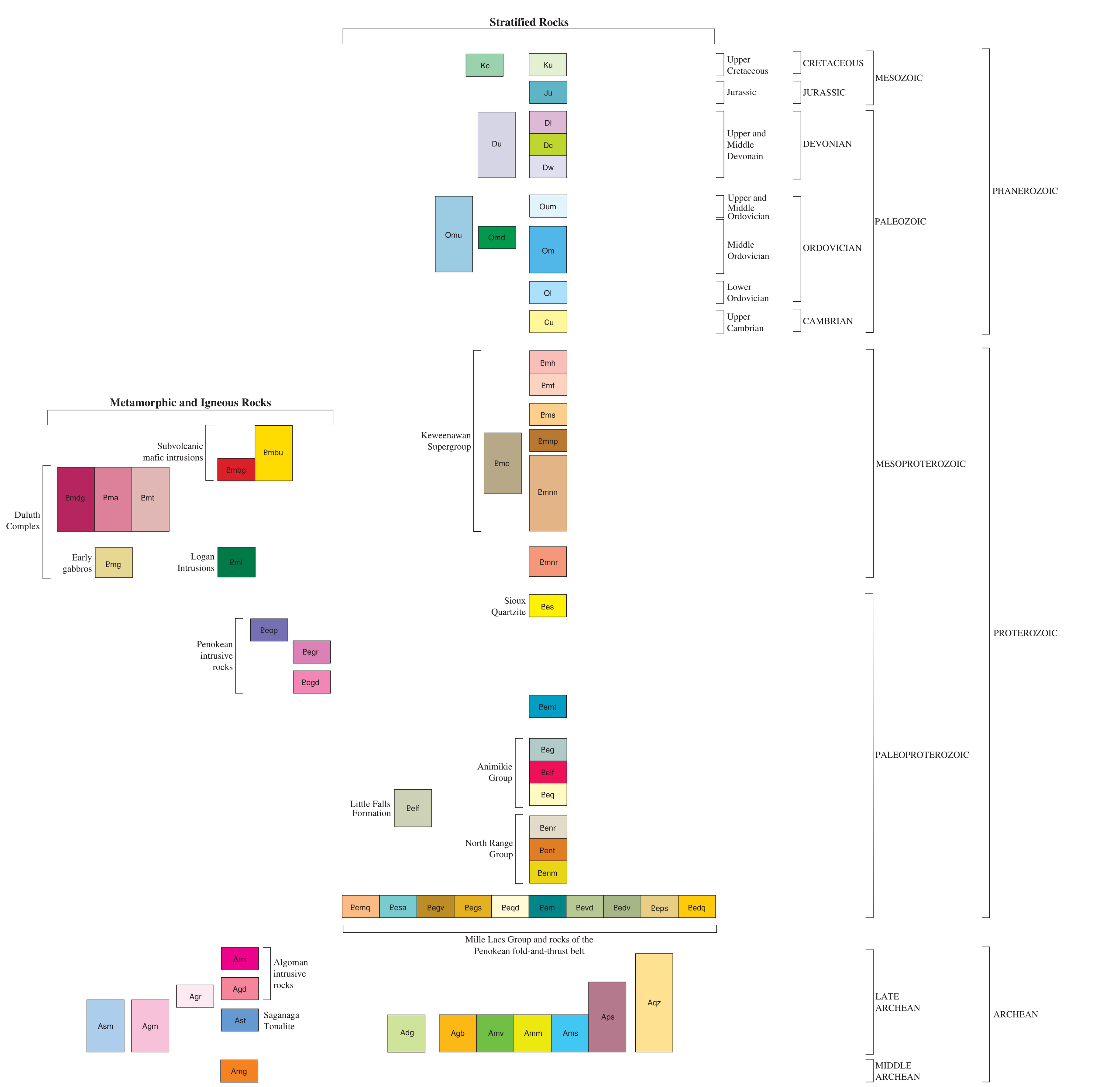


Base modified from 1990 CENSUS TIGER/Line Files of U.S. Bureau of Census (source scale 1:100,000) and Digital Chart of the World (ESRI version).
Lambert Conformal Conic Projection
Standard parallels 33° N and 45° N.

SCALE 1:1,000,000
25 0 25 50 MILES
25 0 25 50 75 KILOMETERS

Geology compiled 2000
GIS compilation and cartography by Joyce Meints; digital cartography by Philip Heywood

CORRELATION OF MAP UNITS



SOURCES OF GEOLOGIC MAPPING USED TO COMPILE THIS MAP

DIGITAL MAPPING—Numbers refer to areas shown on map above.

1 Jirsa, M.A., Chandler, V.W., and Runkel, A.C., 1999, Bedrock geologic map of northwestern Minnesota: Minnesota Geological Survey Miscellaneous Map Series, Map M-92, scale 1:200,000.
2 Chander, V.W., Jirsa, M.A., and Morey, G.B., 1997, Mineral potential assessment of northern St. Louis County, southeastern Koochiching County and northeastern Itasca County, Minnesota: Minnesota Geological Survey Open-File Report 97-5, 9 pls., scale 1:62,000; final report, 26 p.
3 Peterson, D.M., and Jirsa, M.A., compilers, 1999, Bedrock geologic map and mineral exploration data, western Vermilion district, St. Louis and Lake Counties, northeastern Minnesota: Minnesota Geological Survey Miscellaneous Map Series, Map M-98, scale 1:48,000.
4 Jirsa, M.A., Boerboom, T.J., and Morey, G.B., 1998, Bedrock geologic map of the Virginia Horn, Mesabi Iron Range, St. Louis County, Minnesota: Minnesota Geological Survey Miscellaneous Map Series, Map M-85, scale 1:48,000.
5 Miller, J.D., Jr., and Chandler, V.W., 1999, Bedrock geologic map of the central Duluth Complex and the western part of the Beaver Bay Complex, Lake and St. Louis Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map Series, Map M-101, scale 1:100,000.
6 Boerboom, T.J., Southwick, D.L., and Severson, M.J., 1999, Bedrock geology of the Aitkin 30 x 60 minute quadrangle, east-central Minnesota: Minnesota Geological Survey Miscellaneous Map Series, Map M-99, 2 pls., scale 1:100,000.
7 Boerboom, T.J., Southwick, D.L., and Severson, M.J., 1999, Bedrock geology of the Mille Lacs 30 x 60 minute quadrangle, east-central Minnesota: Minnesota Geological Survey Miscellaneous Map Series, Map M-100, 2 pls., scale 1:100,000.
8 Meyer, G.N., project manager, 1995, Geologic atlas of Stearns County, Minnesota: Minnesota Geological Survey County Atlas Series, Atlas C-10, Pt. A, 7 pls., scales 1:100,000 and 1:200,000.
9 Jirsa, M.A., Chandler, V.C., Cleland, J.M., and Meints, J.P., 1995, Bedrock geologic map of east-central Minnesota: Minnesota Geological Survey Open-File Report 95-1, 2 pls., scale 1:100,000.
10 Mossler, J.H., and Tipping, R.G., compilers, 2000, Bedrock geology and structure of the seven-county Twin Cities Metropolitan Area, Minnesota: Minnesota Geological Survey Miscellaneous Map Series, Map M-104, scale 1:125,000.
11 Hobbs, H.C., project manager, 1995, Geologic atlas of Rice County, Minnesota: Minnesota Geological Survey County Atlas Series, Atlas C-9, Pt. A, 6 pls., scale 1:100,000.
12 Setterholm, D.R., project manager, 1998, Geologic atlas of Goodhue County, Minnesota: Minnesota Geological Survey County Atlas Series, Atlas C-12, Pt. A, 6 pls., scale 1:100,000.
13 Bloomgren, B.A., 1993, Bedrock geology of Waseca County, Minnesota: Minnesota Geological Survey Miscellaneous Map Series, Map M-73, 3 pls., scale 1:62,500 and smaller.
14 Mossler, J.H., project manager, 1998, Geologic atlas of Mower County, Minnesota: Minnesota Geological Survey County Atlas Series, Atlas C-11, Pt. A, 6 pls., scale 1:100,000.
15 Mossler, J.H., project manager, 1995, Geologic atlas of Fillmore County, Minnesota: Minnesota Geological Survey County Atlas Series, Atlas C-8, Part A, 5 pls., scale 1:100,000.
16 Runkel, A.C., 1996, Bedrock geology of Houston County, Minnesota: Minnesota Geological Survey Open-File Report 96-4, 3 pls., scale 1:100,000; text, 13 p.
17 Morey, G.B., 1999, unpublished geologic map of the Mesabi iron range, northern Minnesota: Minnesota Geological Survey file map, scale 1:100,000.

NONDIGITAL MAPPING

Morey, G.B., 1996, compiler, Geologic map of Minnesota, bedrock geology: Minnesota Geological Survey State Map Series, Map S-20 digital version 2, scale 1:1,000,000 and references therein.

Every reasonable effort has been made to ensure the accuracy of the factual data on which this map interpretation is based; however, the Minnesota Geological Survey does not warrant or guarantee that there are no errors. Users may wish to verify critical information; sources include both the references listed here and information on file at the offices of the Minnesota Geological Survey in St. Paul. In addition, effort has been made to ensure that the interpretation conforms to sound geologic and cartographic principles. No claim is made that the interpretation shown is rigorously correct, however, and it should not be used to guide engineering-scale decisions without site-specific verification.

DIAGRAM SHOWING GEOLOGIC RELIABILITY BASED ON DENSITY OF BEDROCK OUTCROP

DESCRIPTION OF MAP UNITS

MESOZOIC ROCKS

Ku Cretaceous rocks, undivided—Dakota, Graneros, Greenhorn, Carlile, Niobrara, and Pierre formations and their nonmarine equivalents in northwestern, southwestern, and southeastern Minnesota.

Kc Coleraine Formation—Jasper-pebble conglomerate, sandstone, and shale of diverse origin on the Mesabi range of northern Minnesota, and unnamed sandstone and shale of nonmarine to marine origin in east-central Minnesota.

Ju Jurassic rocks, undivided—Unnamed units of green, gray, brown, and red shale, white to tan micritic limestone and dolostone, and white, fine- to coarse-grained sandstone and siltstone; unit contains nodules of chert and gypsum.

PALEOZOIC ROCKS

Du Devonian rocks, undivided—Limestone, dolomitic limestone, and dolostone of the Cedar Valley and Wapsipinicon Groups.

Dl Lithograph City Formation, Coralville Formation and Hinckle and Eagle City Members of the Little Cedar Formation (Cedar Valley Group), undivided—Limestone, dolostone, and lesser amounts of shale.

Dc Chickasaw Member of the Little Cedar Formation (Cedar Valley Group)—Light-gray to medium-gray shale and silty shale.

Dw Bassett Member of the Little Cedar Formation (Cedar Valley Group) and Pinicon Ridge and Spillville Formations (Wapsipinicon Group)—Dolostone and shaly dolostone.

Oum Upper and Middle Ordovican rocks, undivided—Limestone and shaly limestone of the Maquoketa and Dubuque Formations, and limestone and dolostone of the Galena Group in the Hollandale embayment of southeastern Minnesota.

Omu Middle and Upper Ordovician rocks, undivided—Sandstone and shaly sandstone of the Winnipeg Formation and limestone and dolomitic limestone of the Red River Formation along the east edge of the Williston Basin in northwestern Minnesota.

Om Middle Ordovician rocks, undivided—Decorah Shale; limestone of the Platteville Formation; shaly rocks of the Glenwood Formation; and St. Peter Sandstone in the Hollandale embayment of southeastern Minnesota.

Omd Decorah Shale (Middle Ordovician)—Light-greenish-gray shale and lesser amounts of coquinoid limestone, especially in the upper half of the formation. Mapped as a separate unit where possible.

Ol Lower Ordovician rocks, undivided—Shakopee and Oneota Formations of the Prairie du Chien Group in the Hollandale embayment of southeastern Minnesota. Unit consists dominantly of dolostone and dolomitic limestone. The Shakopee also contains intervals of quartz arenite, including a pronounced basal unit named the New Richmond Member.

Ꞓu Upper Cambrian rocks, undivided—Jordan Sandstone; dolomitic, glauconitic, and silty glauconitic rocks of the St. Lawrence and Franconia Formations; Ironton and Galesville Sandstones; sandy and shaly rocks of the Eau Claire Formation; and the Mt. Simon Sandstone.

MESOPROTEROZOIC ROCKS

Ꝑmh Hinckley Sandstone—Buff to tan quartz arenite of lacustrine and eolian origin.

Ꝑmf Fond du Lac Formation—Red to dark-brown shale, feldspathic sandstone, and arkose of fluvial origin. Includes the Oldenberg Point Member, a pronounced basal unit of quartz-pebble conglomerate in the Duluth area.

Ꝑms Solor Church Formation—Dark-red to dark-brown shale, siltstone, and lithic sandstone of fluvial origin in Scott and Carver Counties; metamorphosed to zeolite facies.

Ꝑmc Chengwatana Volcanic Group—Basalt and related volcanogenic and interflow sedimentary rocks in east-central Minnesota.

North Shore Volcanic Group.

Ꝑmnp *Schroeder-Lutsen basalts*—Predominantly ophitic olivine tholeiitic basalt unconformably over older, normally polarized volcanic rocks. Based on its stratigraphic position and geochemical affinities, the unit may be correlative with the Lake Shore traps of northern Michigan .

Ꝑmnn *Normally polarized volcanic rocks, undivided*—Basalt, andesitic basalt, rhyolite, and related volcanogenic interflow sedimentary rocks along and inland from the North Shore of Lake Superior.

Ꝑmnr *Reversely polarized volcanic rocks, undivided*—Mixed tholeiitic diabasic and porphyritic basalt, trachybasalt, and rhyolite in far northeastern Minnesota and porphyritic and diabasic basalt near Duluth. Includes units of a basal quartz arenite, Puckwunge Sandstone and Nopeming Formation, in northeastern Minnesota and near Duluth, respectively.

Subvolcanic mafic rocks, undivided.

Ꝑmbu *Beaver Bay Complex and other named and unnamed gabbroic-troctolitic intrusions*—Includes a number of other intrusions in a variety of dikes and sills such as the Endion sill and the Pigeon River Intrusions.

Ꝑmbg *Selected granophyric and leuco-granitic phases of troctolitic-gabbroic intrusions in the Beaver Bay Complex.*

Duluth Complex.

Ꝑmdg *Felsic series*—Granophyric granite and related felsic rocks.

Ꝑmt *Troctolitic and gabbroic cumulate rocks*—Constitute at least nine named and several unnamed intrusions.

Ꝑma *Anorthositic series*—Plagioclase-rich gabbroic cumulates and related rocks.

Ꝑmg *Early gabbros*—Gabbro and related rocks in northeastern Minnesota that have petrologic affinities to the Logan Intrusions.

Ꝑml Logan Intrusions—Diabase, porphyritic diabase, gabbro, and related felsic sills and dikes.

PALEOPROTEROZOIC ROCKS

Ꝑes Sioux Quartzite—Red quartzite of fluvial to possibly marginally marine origin. Includes quartz-pebble conglomerate, claystone (catlinite, also called pipestone), a basal (rhyolite) pebble conglomerate in Pipestone County, and a basal (granite, quartz, chert, iron-formation) conglomerate in Nicollet County on the Minnesota River.

Ꝑeop Post-tectonic intrusions of the Penokean orogen—Small stocks of olivine pyroxenite in Morrison County; small plutons of hornblende-rich diorite and gabbro that contain layers and lenses of nelsonite, pyroxenite, and anorthosite in Todd County.

Ꝑegr Late-tectonic intrusions of the Penokean orogen—Includes the St. Cloud and Rockville Granites and Reformatory granodiorite of east-central Minnesota, the Section 28 granite, the Cedar Mountain Complex, and other unnamed intrusions exposed along the Minnesota River Valley in southwestern Minnesota.

Ꝑegd Syntectonic intrusions of the Penokean orogen—Includes the Pierz Granite, the Freedhem and Bradbury Creek Granodiorites, and several unnamed intrusions of granite, granodiorite, tonalite, and gabbro in east-central Minnesota.

Ꝑemt Unnamed schistose, volcanic, and hypabyssal rocks of mafic composition and volcanic, volcaniclastic, and intrusive rocks of felsic composition—May be correlative with rocks of the Wisconsin magmatic terranes.

Animikie Group.

Ꝑeg *Shale, siltstone, feldspathic graywacke, and associated volcaniclastic rocks*—Includes the Rove Formation in Cook County, the Virginia Formation in St. Louis, Itasca, and Lake Counties, and the Thomson Formation in Carlton County.

Ꝑeif *Iron-formation*—Includes the Gunflint Iron Formation in Cook County and the Biwabik Iron Formation and subjacent units of arenite and conglomerate assigned to the Pokegama Quartzite in Itasca, St. Louis, and Lake Counties. Also includes thin lenses of iron-formation (Remer Member) in the Virginia Formation in Itasca County.

Ꝑeq *Pokegama Quartzite*—Quartz arenite, siltstone, and shale. Shown only in Crow Wing County.

Little Falls Formation.

Ꝑelf Quartz-rich slate, argillite, and schist in the northwestward extent of the unit and coarse-grained metagraywacke garnet-staurolite-schist in the southeastward extent—Unit has an uncertain stratigraphic position relative to other Paleoproterozoic units but is apparently younger than the Mille Lacs and North Range Groups.

North Range Group.

Ꝑenr *Rabbit Lake Formation*—Mudstone, graywacke, iron-rich strata, and associated mafic metavolcanic rocks metamorphosed to the greenschist facies. Includes thin beds of carbonate-silicate iron-formation.

Ꝑent *Trommald Formation*—Carbonate-silicate iron-formation overlain by hematite iron-formation and associated manganese oxide deposits. Also contains substantial quantities of volcanic and hypabyssal rocks of generally mafic composition. Metamorphosed to the greenschist facies.

Ꝑenm *Mahnomen Formation*—Claystone, shale, siltstone, and graywacke metamorphosed to the greenschist facies.

Mille Lacs Group and related rocks of the Penokean fold-and-thrust belt.

Ꝑemq *Quartz arenite, siltstone, and chert-rich dolostone of the Trout Lake Formation in Crow Wing County.*

Ꝑesa *Slate, argillite, and metasiltstone metamorphosed to the lower greenschist facies*—Includes lesser amounts of mafic hypabyssal intrusions, and fragmental mafic volcanic rocks.

Ꝑegv *Graphitic schist, slate, and iron-formation metamorphosed to the lower greenschist facies and related conditions*—Includes substantial quantities of mafic to intermediate igneous rocks.

Ꝑegs *Graphitic schist, phyllite and slate interbedded on a fine scale.*

Ꝑeqd *Quartzite at Dam Lake*—Quartz arenite and sericitic quartz schist; includes a substantial component of mafic volcanic rock fragments.

Ꝑem *Metadiabase, undivided.*

Ꝑevd *Metabasalt, metadiabase, and metasedimentary rocks metamorphosed to lower amphibolite facies*—Includes fragmental volcanic rocks, mafic hypabyssal intrusions, graphitic argillite, and oxide iron-formation.

Ꝑedv *Metabasalt, metadiabase, and metasedimentary rocks metamorphosed to lower greenschist facies*—Includes fragmental volcanic rocks, mafic hypabyssal intrusions, graphitic argillite, and oxide iron formation.

Ꝑeps *Metagraywacke, metasiltstone and a variety of schistose rocks metamorphosed to the amphibolite facies.*

Ꝑedq *Denham Formation*—Quartz arenite and siltstone, oxide iron-formation, marble, mafic hypabyssal intrusions and fragmental volcanic rocks metamorphosed to the staurolite grade of the amphibolite facies.

LATE ARCHEAN ROCKS

Ami Post-tectonic mafic intrusions—Gabbro, peridotite, pyroxenite, and their metamorphic equivalents. Unit also includes small intrusive complexes of anorthosite, gabbroic anorthosite, and anorthositic gabbro. Generally characterized by pronounced magnetic signatures.

Agd Multiphase intrusions of hornblende-pyroxene-bearing and biotite-bearing monzonite, monzodiorite, diorite, syenite, and granodiorite—Typically postdates regional metamorphism and deformation associated with the Algoman orogen.

Agr Syntectonic to pretectonic granitoid rocks—Granite and granodiorite of the Vermilion Granitic Complex, the Giants Range and Bemidji batholiths, as well as smaller intrusions of tonalite and monzonite of the Algoman orogen in northern Minnesota. Also includes the Odessa, Sacred Heart, and Fort Ridgely Granites exposed along the Minnesota River Valley in southwestern Minnesota.

Agm Granite-rich migmatite—Granitic gneiss, paragneiss, schist, and migmatite in the Vermilion Granitic Complex and other parts of extreme northern Minnesota. Grades into granitoid rocks.

Ast Saganaga Tonalite of northeastern Minnesota—Emplaced more-or-less contemporaneously with deposition of metasedimentary and metavolcanic rocks.

Asm Paragneiss and schist-rich migmatite—Grades into undivided metasedimentary rocks (unit Ams).

Ams Metasedimentary rocks, undivided—Graywacke, slate, local units of conglomerate, arenite, graphitic slate, fine-grained felsic volcanogenic, and volcaniclastic rocks, lean oxide iron-formation (shown in red) and its metamorphic equivalents. Includes the Knife Lake Group and the Lake Vermilion Formation in northeastern Minnesota.

Amm Mixed metavolcanic rocks—Mafic to felsic volcanic sequences that have variable amounts of felsic volcanogenic and volcaniclastic rocks and lean iron-formation. Includes parts of the Ely Greenstone and the Soudan Iron Formation (shown in red) in northeastern Minnesota.

Amv Mafic metavolcanic rocks—Dominantly basalt that contains thin sedimentary units, including iron-formation (shown in red). Includes parts of the Ely Greenstone and the Newton Lake Formation in northeastern Minnesota. Also includes metabasalt exposed in the Minnesota River Valley.

Agb Anorthosite, gabbroic anorthosite, and anorthositic gabbro of the Mentor mafic intrusive complex in Polk County.

Adg Gabbro, diorite, peridotite, and associated komatiitic flows of the Deer Lake sequence in Itasca County and the upper part of the Newton Lake Formation in Lake and St. Louis Counties.

Aps Paragneiss, schist, and amphibolite—Amphibolite-facies equivalent of units Amv and Ams; locally includes abundant intrusions of unit Agr.

Aqz Felsic to intermediate volcanic and volcaniclastic rocks, mica schist, phyllite, and granitoid rocks—Variably and calcareously deformed. Units form aeromagnetic "quiet zone" and probably contain some rocks of Paleoproterozoic age.

MIDDLE ARCHEAN AND OLDER ROCKS

Amg Migmatitic gneiss, amphibolite, and granite—Montevideo and Morton Gneisses (3,600–3,000 m.y.) in the Minnesota River Valley, southwestern Minnesota; McGrath Gneiss (2,750 m.y.) east of Mille Lacs Lake; components of Hillman Migmatite southwest of Mille Lacs Lake; and Sartell Gneiss in Stearns County. Inferred to include various younger rocks, including granitoid intrusions in the Hillman Migmatite and pillowed basalt in poorly exposed areas of southwestern Minnesota.

Geologic contact—Located principally by inference or by airborne magnetic surveys except in the few places where the contact is exposed.

Inferred trace of a steeply dipping fault.

Inferred trace of a thrust fault or structural discontinuity that is interpreted to have involved thrust displacement—Teeth are on the upper plate.

Iron-formation.