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MINNESOTA GEOLOGICAL SURVEY
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SAND DISTRIBUTION MODEL

By

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2010

INTRODUCTION

The sand and gravel deposits of Minnesota are products of a long and complex history of multiple glacial events that makes mapping of these potential aquifers difficult. However, establishing the location and characteristics of sand and gravel aquifers is an important step toward their wise use and protection. In Chisago County, this project employed a process that combined the understanding of a geologist with the data-handling ability of a geographic information system (GIS) to create models showing the distribution of Quaternary sand and gravel deposits that may be aquifers. The three-dimensional models relate aquifers to the glacial events that formed them. Although the models and interpretations are based on the best available data, they are unavoidably incomplete due to a lack of data in some areas.

The distribution of sand (which in the following text implies sand and gravel) at the land surface was mapped by the geologist from exposures, shallow drill holes, soil maps, and landforms. In contrast, interpreting sand distribution in the subsurface relied primarily on well records, scientific drill core, and drill cuttings. Sand distribution models were based on the assessment of these data, consideration of the processes that deposited the glacial sediment, and an understanding of the glacial history.

The unconsolidated Quaternary sediments that overlie the bedrock in Chisago County vary greatly in character and thickness. These deposits are largely the result of more than six distinct glacial ice advances during the Pleistocene Epoch (Plate 4), so most of the Quaternary aquifers within Chisago County consist of sand and gravel beds laid down by meltwater that emanated from these glaciers. Layers of unsorted sediment deposited directly from the ice, termed "till," as well as fine-grained bedded sediment deposited in ponded meltwater in front of the glaciers, form confining layers (aquitards) that enclose the aquifers. The till layers left by each ice sheet tend to be more laterally persistent than the sand layers, as ice usually spread across the entire county, whereas meltwater streams that deposited the sand and gravel were generally confined to drainages at the lower elevations of the evolving landscape. Sand and gravel may be deposited by both an advancing glacier and a retreating glacier of the same cycle, thus till from an ice advance may bury its own sand and gravel as well as material deposited during a previous glacial event. The sand and gravel bodies depicted in this report are associated with the underlying till or lake sediment (except for those at the land surface; Fig. 1).

Glacial ice and meltwater not only deposited sediments, but also eroded older, underlying sediments, creating a very disturbed "layer cake." A new layer of sand or till could fill a void eroded into an older layer or could completely take the place of an older layer, given sufficient erosion. The net effect of this depositional and erosional activity is that sand bodies that provide water to wells in Chisago County tend to be discontinuous. Over relatively short distances in most directions, the extent and thickness of any given aquifer is difficult to predict. In order to address this problem, 51 closely spaced (1 kilometer) cross section lines were generated in a west to east direction (Fig. 2). Along these lines, water well records, and records of scientific and engineering test holes (Plate 1, *Data-Base Map*), were used by the geologist to identify contacts between units in the subsurface. The results from the cross section analysis were compiled digitally into grids of top and bottom surfaces and grid thicknesses for each interpreted unit of till and sand. Final interpretations along five of these cross sections are shown on Plate 4.

Till is generally described as "clay" by well drillers. Where two clay (till) layers related to different depositional events were not separated by a sand layer, their contact was recognized by a change in the driller's description of the clay's texture (for example clay/sandy clay/clay and gravel), density, or color. Using the available data, contact lines were drawn along each cross section, with each line representing the base of a unit of sand and gravel or till. GIS software was used to extract elevation values from vertices along each unit line, and convert those into a gridded elevation surface representing the distribution of the unit over the county. The till and sand surfaces were iteratively modified until the geologist was confident that they adequately represented the areal distribution and stratigraphic interpretation derived from the water well data. When the till and sand surface grids representing the base of each unit were final, they were processed through GIS raster calculations to create top and bottom surfaces and a thickness for each geologic unit. The result is a three-dimensional geologic model of tills and sands for the county. The more extensive sands portrayed by the geologic model are shown in Figures 3 through 8. Note that contours showing thickness of sand and gravel units do not close within the outline of each unit. This is an artifact of the GIS processing of surfaces. The figures show sand units ranging from the youngest sands at the land surface to buried, progressively older sands (Fig. 1).

Where saturated, these sand bodies are aquifers. Their capacities for water yield depend on the extent and thickness of the body, as well as factors such as sediment coarseness, degree of sorting, and consolidation. In many places two or more of these sand units form a single aquifer where they are juxtaposed with no intervening till layer (see cross sections on Plate 4). Data from other, less extensive sand bodies, as well as from the eight till/fine-grained lake sediment bodies that were created in the geologic model, are not shown on the printed map plates, but are provided with the digital files for this atlas.

The geologic model should be considered a probability map for the occurrence and approximate thicknesses of major sand bodies. The model does not guarantee sand and gravel will be found at all places shown, nor does it preclude them being found where they are not shown. In areas where numerous wells penetrated the shallower sands, too much data were available and much of the small detail could not be shown at the map scale. Elsewhere, sands that were too thin or did not extend to neighboring cross sections do not appear on the figures. Because wells typically do not penetrate the complete thickness of sand layers, drillers' logs commonly underreport sand body thickness. As a result, some of the sands shown on the cross section (but not necessarily on the final sand distribution map) may be thicker and more widespread than they are portrayed. At increasing depths in the stratigraphic section, data availability diminishes and delineated sand bodies could be more or less discontinuous than shown.

In many parts of Chisago County water wells do not extend through the full thickness of the Quaternary deposits. The cross sections on Plate 4 indicate that the characteristics of deeper Pleistocene deposits cannot be differentiated in many places (Fig. 9). However, where deep drill holes occur locally, thicker sands are commonly present. Additional sand bodies, or extensions of those mapped, are undoubtedly present in these undifferentiated parts of the Pleistocene section. In spite of these limitations, the geologic model provides a realistic interpretation of where and what kind of geologic units would be encountered in the subsurface of Chisago County. However, given the limits of the data, as noted above, the model should be used as a guide and should not preclude further site-specific investigations or inspection of individual well logs.

Figure 1. Stratigraphic position of sand and gravel bodies shown on the sand distribution diagrams (Figs. 3 through 8)—Undifferentiated Pleistocene sediment (Fig. 9) may include any unit older than the New Brighton formation (Plate 4).

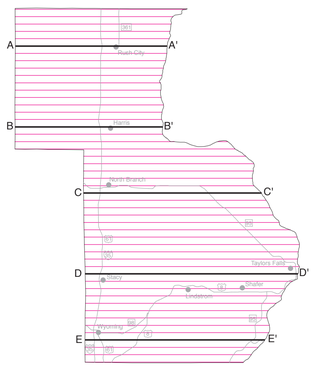


Figure 2. Cross section location map—Location of the 51 cross sections, constructed at regular 0.6 mile (1 kilometer) intervals, used to create a three-dimensional model of the Quaternary deposits of Chisago County. Cross sections A–A' through E–E' appear on Plate 4, *Quaternary Stratigraphy,* and their locations are also shown on Plate 3, *Surficial Geology.*

CONTOURS FOR FIGURES 3 THROUGH 8

Thickness of a sand and gravel unit contoured at 20 foot (6 meter) intervals.

- 20
- 40
- 60
- 80
- 100
- 120
- 140 and greater

Note: Contour lines commonly do not close at the edges of mapped areas. This is an artifact of the digital processing.

DEPTH FOR FIGURES 4 THROUGH 9

- 0–50
- 51–100
- 101–150
- 151–200
- 201–250
- 251–300
- 301–350
- 351–400

Depth in feet from the land surface to the top of a sand and gravel unit (depth from the land surface to the top of undifferentiated sediment is shown on Figure 9).

SCALE 1:300 000

5 0 5 10 MILES

5 0 5 10 KILOMETERS

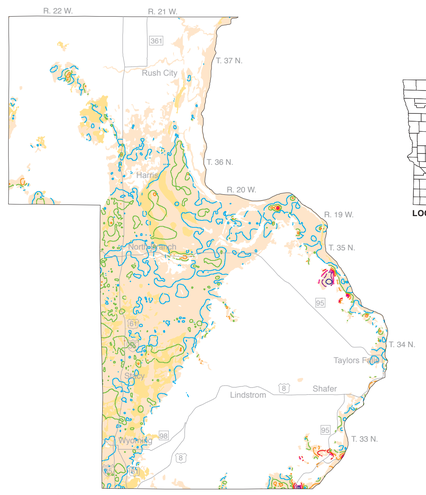


Figure 3. Surficial sand and gravel—Model-generated map showing the extent and thickness of sand and gravel bodies occurring at the land surface (cream colored) or below peat (orange) in Chisago County. Includes units Qe, Qa, Qf, Qws, Qwg, Qwl, Qwr, Qbs, Qbg, Qns, Qno, Qni, Qel, and Qei from Plate 3, *Surficial Geology.* The surficial aquifer of the county is that portion of these sand and gravel bodies that is below the water table.

LOCATION DIAGRAM

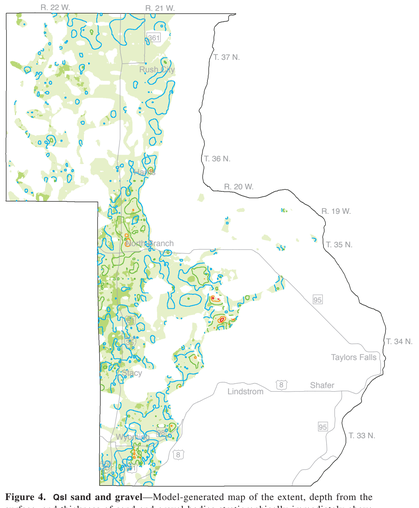


Figure 4. Qsl sand and gravel—Model-generated map of the extent, depth from the surface, and thickness of sand and gravel bodies stratigraphically immediately above laminated silt and clay or fine-textured till of unit Qlc. The nearly continuous strip of sand from Rush City to Wyoming was laid down primarily in glacial Lake Lind II. The large gap mapped in the sand body east of Stacy is likely due to the lack of data in the area. The more discontinuous bodies in the northwest part of the county were likely laid down by streams draining into glacial Lake Lind from the retreating Automba phase of the Superior lobe, but may include some pro-glacial sediment from the advancing Grantsburg sublobe.

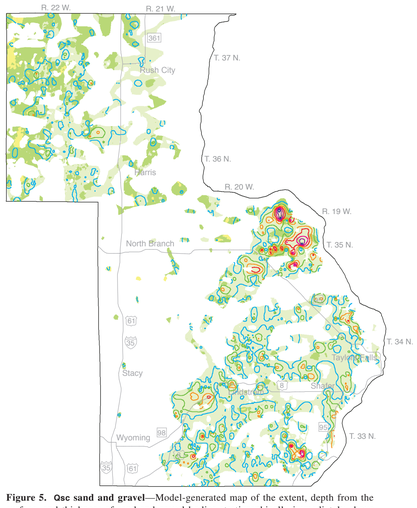


Figure 5. Qse sand and gravel—Model-generated map of the extent, depth from the surface, and thickness of sand and gravel bodies stratigraphically immediately above (mostly) sandy till of unit Qcr. Mostly fluvial or deltaic sediment deposited by meltwater from the receding St. Croix phase and advancing Automba phase of the Superior lobe. The thicker deposits are fans laid down at the ice margin.

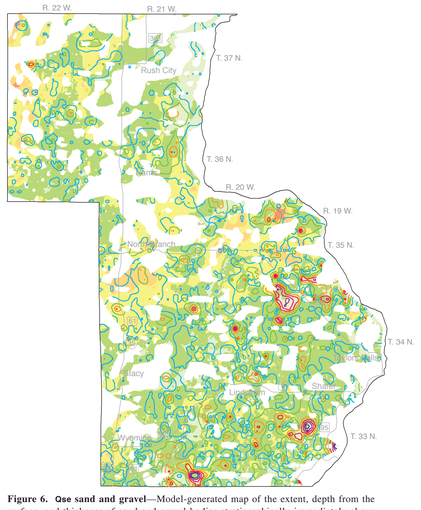


Figure 6. Qse sand and gravel—Model-generated map of the extent, depth from the surface, and thickness of sand and gravel bodies stratigraphically immediately above (mostly) sandy till of unit Qce. Mostly fluvial sediment deposited by meltwater from the receding Emerald phase and advancing St. Croix phase of the Superior lobe. The thicker deposits are fans laid down at the ice margin.

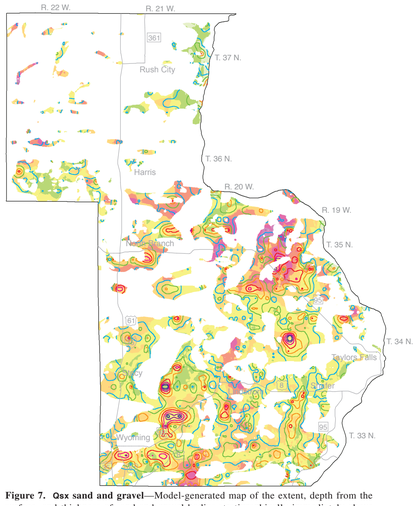


Figure 7. Qsx sand and gravel—Model-generated map of the extent, depth from the surface, and thickness of sand and gravel bodies stratigraphically immediately above (mostly) fine-textured till of unit Qxt. Mostly pro-glacial outwash of the Emerald phase of the Superior lobe, but includes older deposits.

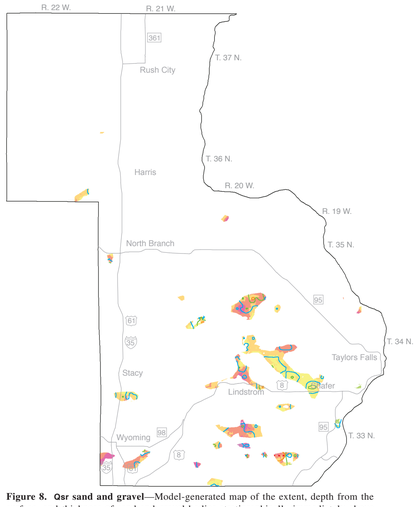


Figure 8. Qsr sand and gravel—Model-generated map of the extent, depth from the surface, and thickness of sand and gravel bodies stratigraphically immediately above (mostly) sandy till of unit Qrt.

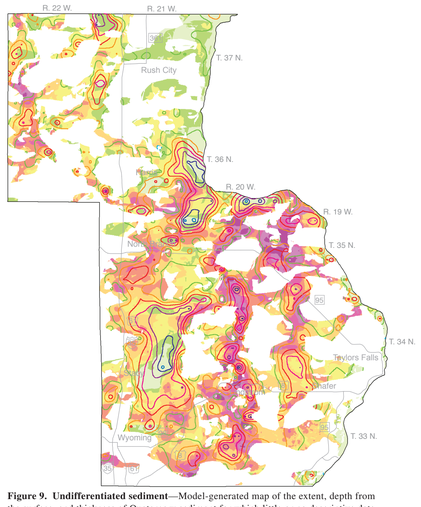


Figure 9. Undifferentiated sediment—Model-generated map of the extent, depth from the surface, and thickness of Quaternary sediment for which little or no descriptive data are available, contoured at 50-foot (15-meter) intervals. In white areas, numerous data exist and the geology between the land surface and bedrock is generally known.

CONTOURS FOR FIGURE 9

- 0
- 50
- 100
- 150
- 200
- 250
- 300
- 350

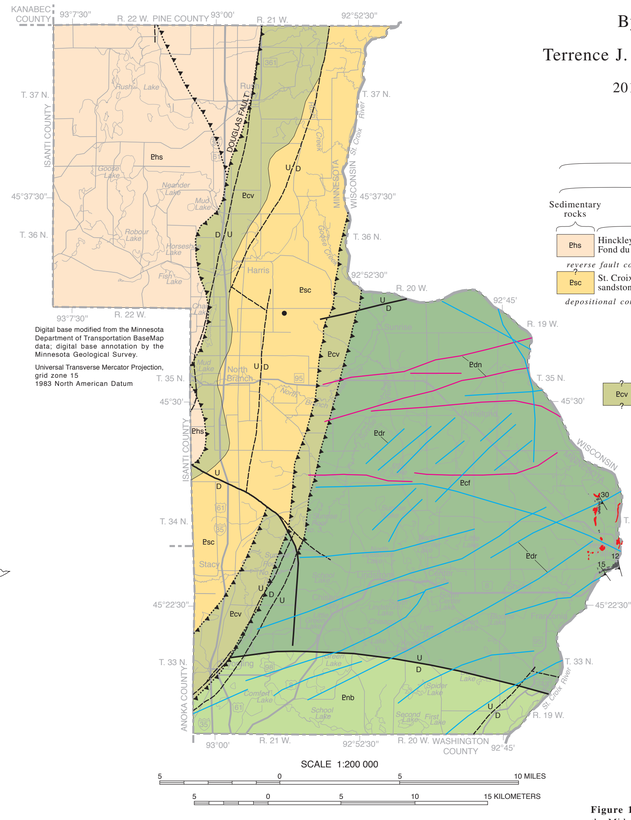
Thickness of undifferentiated sediment.

PRECAMBRIAN BEDROCK GEOLOGY

By

Terrence J. Boerboom

2010



Digital base modified from the Minnesota Department of Transportation BaseMap data; digital base annotation by the Minnesota Geological Survey.

Universal Transverse Mercator Projection, grid zone 15
1983 North American Datum

SCALE 1:200 000

5 0 5 10 MILES

5 0 5 10 15 KILOMETERS

CORRELATION OF MAP UNITS

MIDCONTINENT RIFT SYSTEM

- Keweenawan Supergroup
  - Sedimentary rocks
    - Ehs — Hinckley Sandstone and Fond du Lac Formation
    - *reverse fault contact*
    - Esc — St. Croix Horst sandstone
    - *depositional contact*
  - Volcanic rocks
    - Enb — North Branch volcanics
    - *volcanic unconformity*
    - Ecf — Clam Falls volcanics
    - Ecv — Chengwatana volcanics
  - Intrusive rocks
    - Edn — Diabase dike, normally polarized
    - Edr — Diabase dike, reversely polarized
    - *reverse fault contact*
    - *intrusive contact*

MESOPROTEROZOIC

MAP SYMBOLS

- **Geologic contact**—Located from aeromagnetic data.
- **Outcrop of Precambrian bedrock**—Mapped for this study.
- **Outcrop of Precambrian bedrock**—From Berkey (1898).
- **Strike and dip of volcanic flow layering.**
- **Location of bore hole with downhole video log.**
- **Fault with reverse sense of movement**—Teeth on upthrown side. Interpreted from aeromagnetic data; buried beneath Paleozoic bedrock.
- U D **Dip-slip or strike-slip fault in Precambrian bedrock**—Interpreted from aeromagnetic data; D–downthrown side; U–upthrown side.
- U D **Dip-slip or strike-slip fault that affects Paleozoic bedrock (Plate 2)**—May correspond to older Precambrian faults locally; D–downthrown side; U–upthrown side.
- **Structural dome (shown only on Fig. 2).**

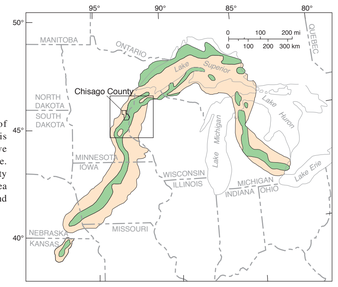
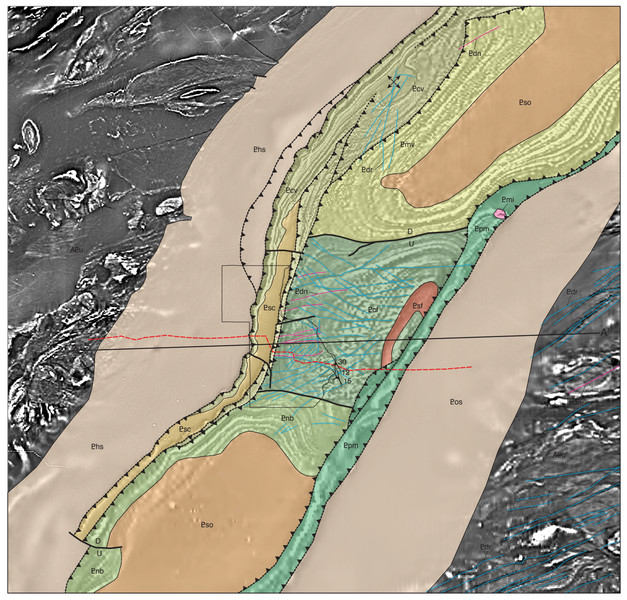


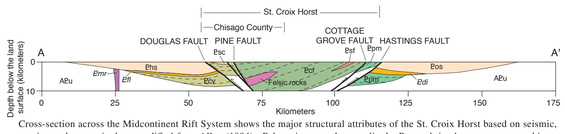
Figure 1. Map showing the extent of the Midcontinent Rift System. Purple is dominantly volcanic and lesser intrusive igneous rocks, tan is dominantly sandstone. The approximate location of Chisago County is shown; box denotes the approximate area of Figure 2. Modified from Ojakangas and Dickas (2002).



Ehs Eos	Bayfield Group sedimentary rocks (the Hinckley Sandstone in Minnesota [Ehs] and the equivalent Orienta Sandstone in Wisconsin [Eos]).
Ef Edi	Sandstone (shown only on cross section); the Fond du Lac Formation in Minnesota [Ef] and the equivalent Devil's Island Sandstone in Wisconsin [Edi])
Esc	St. Croix Horst sandstone (informal name).
Eso	Oronto Group sedimentary rocks (conglomerate, shale, and sandstone).
Emi	Mafic intrusion.
Emr	Reversely-polarized mafic to ultramafic intrusion buried beneath unit Ehs (shown only on cross section).
Edn	Normally polarized diabase dike.
Edr	Reversely polarized diabase dike.
Enb	North Branch volcanics (dominantly basalt).
Emv	Minong volcanics (dominantly basalt, includes rhyolite and interflow sandstone and conglomerate[1]).
Ecf	Clam Falls volcanics (includes thin units of interflow sedimentary rocks[2]).
Esf	Sedimentary or felsic volcanic rocks near the base of the Clam Falls volcanics.
Ecv	Chengwatana volcanics (dominantly basalt, includes thick interflow conglomerate).
Epm	Powder Mill volcanics (dominantly basalt, includes minor interflow conglomerate and rhyolite[3]).
APu	Archean to Paleoproterozoic crust.

Figure 2. Regional geologic map of the Midcontinent Rift System; modified from Cannon and others (2001) and cross section (below). Background is a gray-scale shaded-relief image of second-vertical derivative aeromagnetic data. Location of an east–west seismic line is shown as a dashed red line.

[1]1,094 million years in age (Zartman and others, 1997).
[2]1,102 million years in age.
[3]1,107 million years in age (Zartman and others, 1997).



Cross-section across the Midcontinent Rift System shows the major structural attributes of the St. Croix Horst based on seismic, gravity, and magnetic data; modified from Allen (1994). Paleozoic strata that overlie the Precambrian basement are too thin to show at this scale (see Plate 2). Faults affecting Paleozoic strata are not shown. Dashed lines represent the dip of volcanic rocks. Location of the cross-section line is shown on Figure 2.

INTRODUCTION

The first bedrock beneath Chisago County is dominated by various Paleozoic sedimentary rock units (Plate 2, *Bedrock Geology*) that form layers of strata deposited on top of older, eroded, Precambrian bedrock. The Precambrian bedrock, which is the subject of this plate, forms an irregular surface of variable elevation, and is locally exposed at the surface in places where higher knobs have been exhumed by erosion of the overlying Paleozoic strata and glacial sediment, near the St. Croix River. In most of the county the Precambrian bedrock is covered by the younger Paleozoic strata, but in some areas, the Precambrian bedrock is the first bedrock unit beneath glacial sediment.

The Precambrian bedrock beneath Chisago County is approximately 1,100 million (1.1 billion) years old. It is part of a suite of rocks known as the Midcontinent Rift System, which is a relatively narrow, approximately north–south trending belt composed dominantly of volcanic and sedimentary rocks, that extends from beneath Lake Superior south along the Minnesota–Wisconsin border, and continues south as far as Kansas (Fig. 1). In the Lake Superior region, including Chisago County, rocks of the Midcontinent Rift System are known as the Keweenawan Supergroup (Morey and Van Schmus, 1988), which is dominated by flood basalts and other volcanic rock types that are generally more dense and magnetic than the typical rocks that make up the earth's crust. These characteristics produce prominent geophysical anomalies that clearly outline the overall extent of the Midcontinent Rift System on a continental scale. Geologic features within the rift are also readily apparent from geophysical data, in particular aeromagnetic maps (Fig. 2).

In the Precambrian basement beneath Chisago County (Fig. 3), basaltic volcanic rocks are predominant in the eastern half of the county, whereas sandstone units are predominant in the western half of the county. Several major faults are recognized on the basis of sharp breaks in aeromagnetic map patterns that continue to the northeast, where the faults are locally exposed in outcrops. The major north–south faults, such as the Douglas Fault, first formed as extensional faults related to rifting, or spreading, of the earth's crust, along which the center of the rift was down-dropped to form a geologic feature known as a graben. As the central graben subsided, or sank, volcanic rocks dominated by flood basalts were erupted into the rift. After volcanic activity had largely ceased, the central graben continued to subside for some time, forming a linear basin into which sand was deposited to form the overlying sandstone units, both on top of the volcanic rocks within the graben, and on older crust adjacent to the central rift axis.

Subsequent to or perhaps partly synchronous with sandstone deposition, the regional stress field acting on the crust changed from extensional to compressional. The later compressional event caused reverse movement along the early extensional faults and uplifted the central portion of the rift approximately 2 to 4 miles (3 to 7 kilometers), bringing rocks that were formerly deeply buried up to a higher level, adjacent to the sandstones that flanked the main rift axis. Subsequent erosion has flattened the Precambrian bedrock and has produced the map pattern we see today, which in general is one of thick sandstone units flanking the central rift axis, and basaltic volcanic rocks dominating the center (Figs. 1, 2). This eroded surface is the one on which the overlying Paleozoic sedimentary strata were deposited.

The uplifted central block of the rift is known as the St. Croix Horst (Fig. 2, cross-section), a well-known feature of the central part of the Midcontinent Rift System in Minnesota and Wisconsin. Calculations based on gravity and magnetic geophysical models as well as seismic data (Fig. 2, red dashed line) show that beneath Chisago County sedimentary rocks adjacent to the central uplifted horst are as much as 2 to 2.5 miles (3 to 4 kilometers) thick, and the volcanic rocks in the central St. Croix Horst are as much as 6 miles (10 kilometers) in thickness (Allen, 1994; Allen and others, 1997).

Based on water well data, several faults that offset the Paleozoic strata have been identified (Plate 1); these do not have sufficient offset to create anomalies in the geophysical data and hence cannot be confidently extended into the underlying Precambrian basement. However, it can be inferred that they either must extend into and affect the Precambrian basement, or that they emanate from pre-existing Precambrian faults that have been slightly reactivated. Most of the major faults in the Precambrian basement are not recognized in the overlying Paleozoic section. Hence the history of faulting is one of major, early faults in the Precambrian basement that were locally reactivated to a small degree subsequent to deposition of the overlying Paleozoic strata.

Diabase dikes, which are thin units of basaltic composition that intruded as molten magma and cooled in place, are inferred from aeromagnetic data, based on the similarity to other areas of the state where there is a known correlation between exposed diabase dikes and linear aeromagnetic anomalies. In Chisago County, the diabase dikes are inferred to have once fed lava flows higher in the sequence that have since been eroded away.

Refer to Boerboom and others (2002) and references therein for a more complete explanation of the Midcontinent Rift System development.

DESCRIPTION OF MAP UNITS

MESOPROTEROZOIC ROCKS

Keweenawan Supergroup

Ehs **Hinckley Sandstone**—Quartz arenite, tan to orange, fine- to medium-grained, well-sorted and well-rounded; composed of about 96 percent quartz (Tryhorn and Ojakangas, 1972). Distribution is based on a subdued and featureless aeromagnetic anomaly, which is continuous with areas to the north in Pine County, where the sandstone is exposed in outcrops.

Esc **St. Croix Horst sandstone** (informal name)—Distribution is inferred from a flat and featureless aeromagnetic anomaly pattern and corresponding second-vertical derivative gravity low. This unit is continuous with an area mapped to the north in Pine County with similar geophysical expression. A drill core there intersected lithic arkosic sandstone that may be similar to, but not necessarily correlative with, the Fond du Lac Formation, which underlies the Hinckley Sandstone (Boerboom and Chandler, 2001). Alternatively, this unit may be correlative with the Solor Church Formation (Morey, 1977), an older sandstone unit that is restricted to the top of the St. Croix Horst, which occurs mostly to the south of Chisago County. A downhole video bore log obtained from within this unit in Chisago County shows that bedding dips 50° to 70° from horizontal, implying that it is part of an eastward-tilted block situated on top of the St. Croix Horst. The sandstone is cut by numerous thin, white veins tentatively identified as calcite, which are at a high angle to bedding. This sandstone starts at 372 feet (113 meters) in depth, beneath Paleozoic sedimentary rocks, and the upper 6 inches (15 centimeters) show evidence of having a paleosol or saprolite developed in it. The western margin may be an eroded depositional edge, whereas the eastern margin is likely truncated by the Pine Fault system.

Edn **Diabase dike, normally polarized.**

Edr **Diabase dike, reversely polarized.**

Enb **North Branch volcanics**—Inferred from aeromagnetic anomaly patterns to be composed dominantly of southwest-dipping mafic lava flows located at the northern margin of a volcanic basin that unconformably overlies the Clam Falls volcanics (Cannon and others, 2001).

Ecf **Clam Falls volcanics**—A thick succession of largely mafic volcanic rocks between the Pine Fault on the west and the Cottage Grove–Lake Owens fault on the east in Wisconsin (Cannon and others, 2001). Outcrops near Taylors Falls consist of thick, coarsely ophitic basalt flows with amygdaloidal fragmental flow tops, and thinner flows of fine-grained intergranular basalt and coarsely porphyritic basalt, which also have amygdaloidal fragmental flow tops. All the exposed flows contain abundant secondary epidote and actinolite, and the upper parts of the flows have amygdules filled with quartz, chlorite, epidote, K-feldspar, and calcite. These mineral assemblages indicate burial depths of approximately 5 miles (7.5 kilometers) prior to uplift of the St. Croix Horst (Wirth and others, 1998). East of Minnesota, near Clam Falls, Wisconsin, the Clam Falls volcanics contain minor rhyolite that yielded a zircon U-Pb age of 1,102 ± 5 million years (Wirth and Gehrels, 1998). Well records indicate the Clam Falls volcanics may include thin units of interflow sandstone.

This unit was traditionally considered to be part of the Chengwatana volcanic group, but based on geophysical anomaly patterns was subdivided and informally termed the Clam Falls volcanics (Cannon and others, 2001). Subsequent to that reinterpretation, the Clam Falls volcanics were once again grouped as part of the Chengwatana volcanics, based on geochemical similarity and ambiguous geophysical data (Nicholson and Cannon, 2003). However, the term Clam Falls is retained here due to biases of the author in interpreting the regional geophysical anomalies.

Ecv **Chengwatana volcanics**—Not exposed in Chisago County, but clearly demarcated by gravity and magnetic data to be continuous with bedrock exposures located in Pine County, approximately 7 miles (11 kilometers) north of Chisago County. Outcrops there are composed of a steeply east-dipping sequence of interlayered ophitic to weakly porphyritic basalt flows and coarse interflow conglomerate units that range from 30 to 50 feet (9 to 15 meters) in thickness (Boerboom and Chandler, 2001; Boerboom and others, 2002). The western margin is juxtaposed against the Hinckley Sandstone along the reverse Douglas Fault; the eastern margin is truncated by the Pine Fault. Unit is overlain by the St. Croix Horst sandstone (unit Esc). Well records also indicate the presence of red sedimentary rocks that are likely thin units of interflow sandstone.

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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.