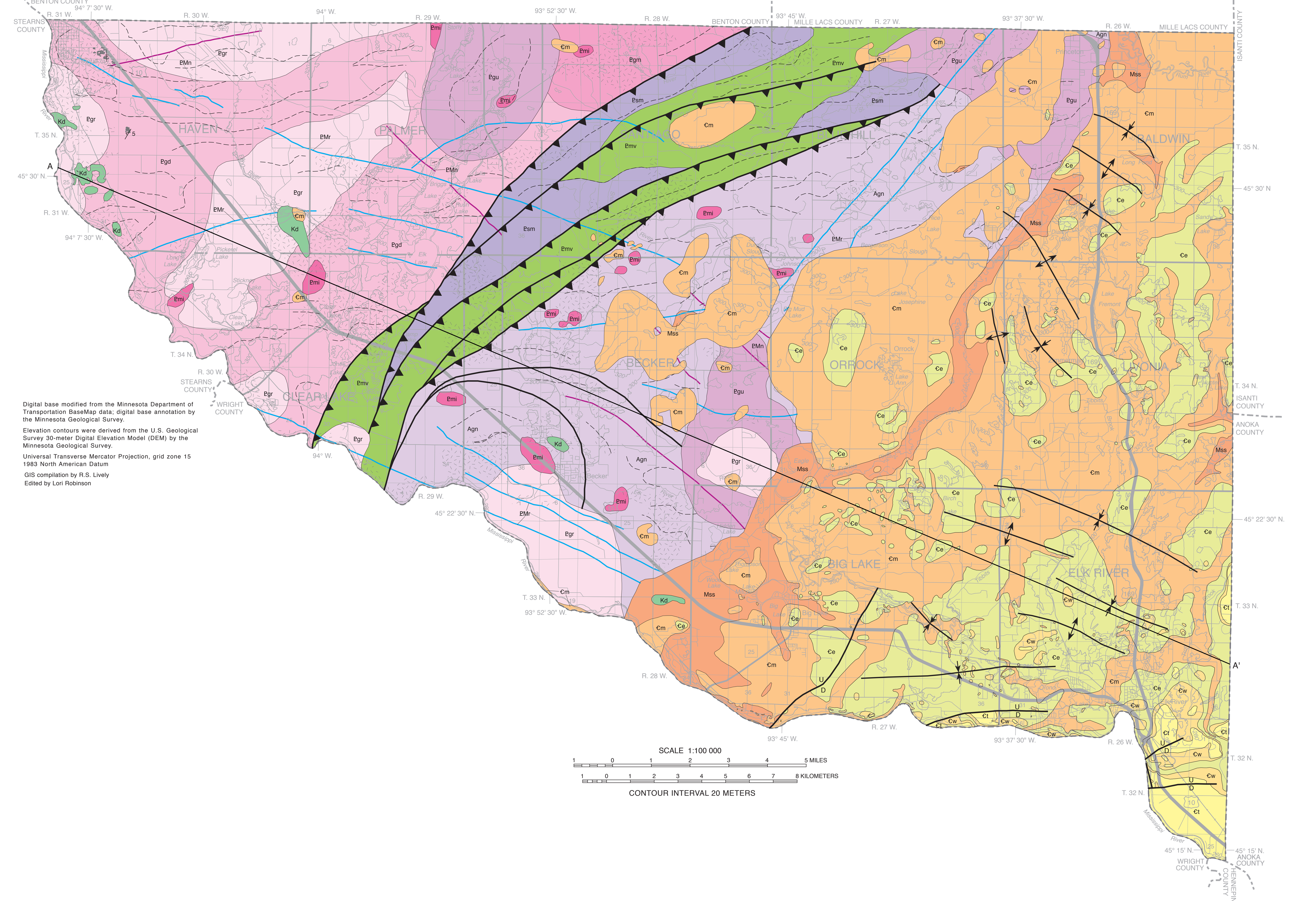
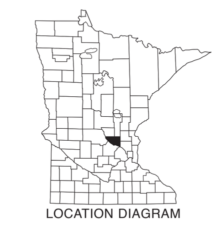
Prepared and Published with the Support of
THE U.S. GEOLOGICAL SURVEY AS PART OF THE 2011 STATE GEOLOGIC MAPPING PROGRAM ELEMENT (STATEMAP)
OF THE NATIONAL COOPERATIVE GEOLOGIC MAPPING PROGRAM, THE SHERBURNE COUNTY BOARD OF COMMISSIONERS,
AND THE MINNESOTA ENVIRONMENT AND NATURAL RESOURCES TRUST FUND
AS RECOMMENDED BY THE LEGISLATIVE-CITIZEN COMMISSION ON MINNESOTA RESOURCES





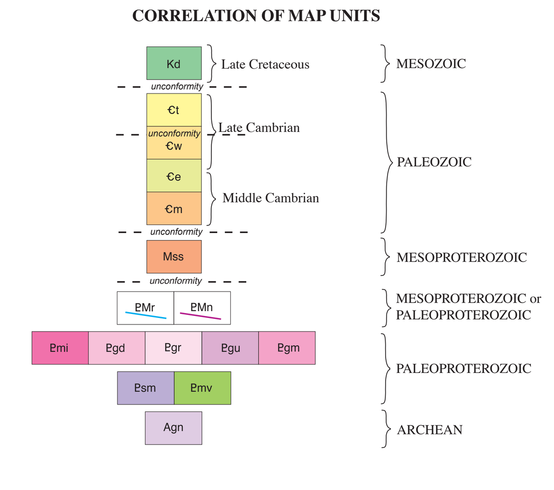
BEDROCK GEOLOGY

By

V.W. Chandler and John H. Mossler

2013

CORRELATION OF MAP UNITS



MAP SYMBOLS

Geologic contact—Approximately located.

Fault—Faults in Paleozoic rocks are interpreted to have had dip-slip movement. Letters indicate relative vertical displacement: U—up, D—down. Faults are concealed by Quaternary sediments and recent alluvium and are inferred from subsurface geologic data supplemented by aeromagnetic and gravity data. Offsets of Paleozoic strata indicate that these faults were rejuvenated during post-Mesoproterozoic time (Fig. 2A). Faults in Precambrian (Mesoproterozoic, Paleoproterozoic, and Archean) rocks are inferred from geophysical data.

Thrust fault, or structural or geophysical discontinuity interpreted to have involved thrust displacement—Teeth are on the inferred upper plate.

Magnetic anomaly trend—Inferred to represent structural grain within some mapped Precambrian units.

Fold—All folds have shallowly dipping limbs.

Axial trace of syncline

Axial trace of anticline

Outcrop

Strike of small, vertical, granitic dike.

5 **Strike and dip of magmatic foliation.**

Saprolite—Soft, decomposed rock derived primarily from the in situ weathering of igneous and metamorphic rocks either from long periods of exposure on a low relief surface or intense weathering during humid tropical to temperate climates. In Sherburne County, saprolite is present in localized areas where it has not been removed by subsequent erosion.

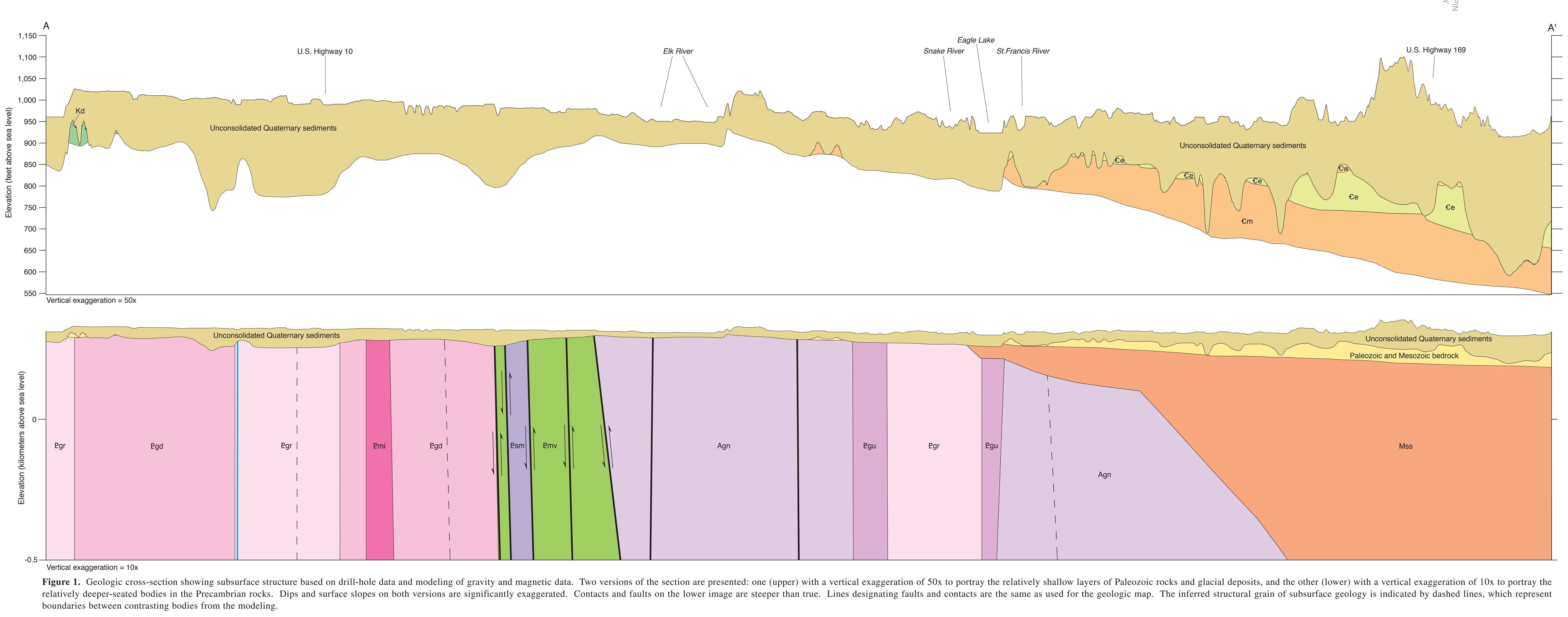


Figure 1. Geologic cross-section showing subsurface structure based on drill-hole data and modeling of gravity and magnetic data. Two versions of the section are presented: one (upper) with a vertical exaggeration of 50x to portray the relatively shallow layers of Paleozoic rocks and glacial deposits, and the other (lower) with a vertical exaggeration of 10x to portray the relatively deeper-seated bodies in the Precambrian rocks. Dips and surface slopes on both versions are significantly exaggerated. Contacts and faults on the lower image are steeper than true. Lines designating faults and contacts are the same as used for the geologic map. The inferred structural grain of subsurface geology is indicated by dashed lines, which represent boundaries between contrasting bodies from the modeling.

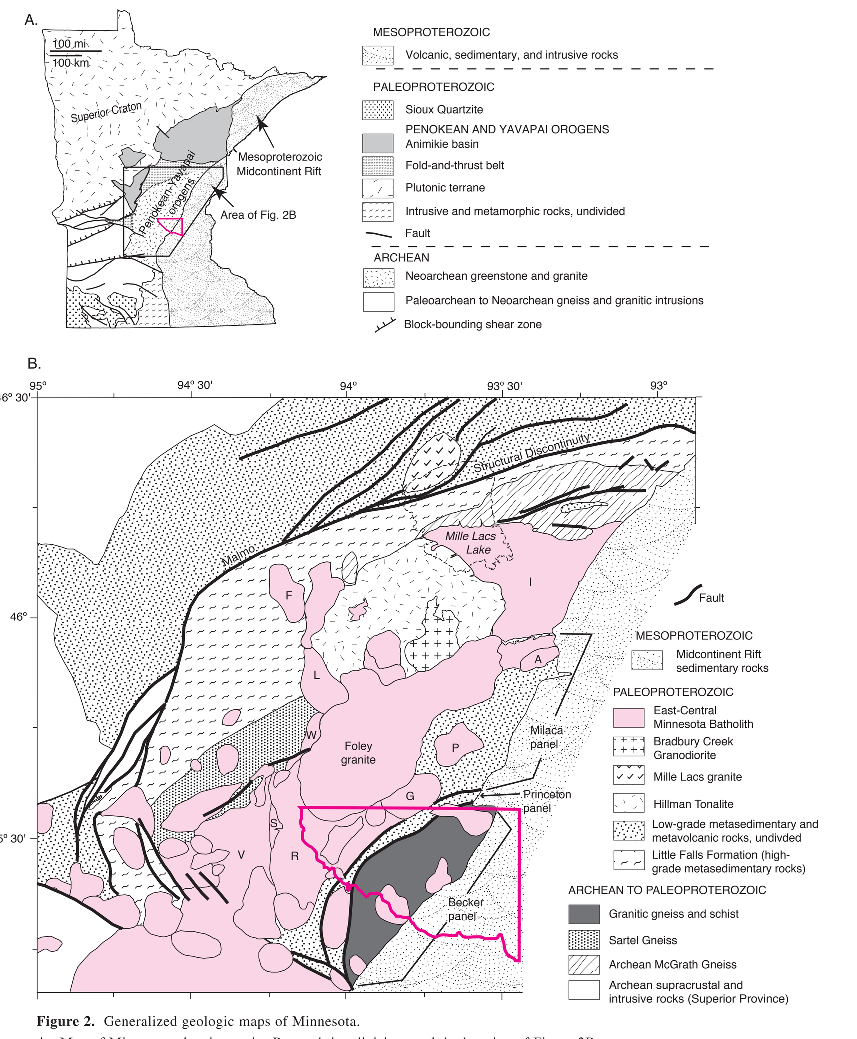


Figure 2. Generalized geologic maps of Minnesota.

A. Map of Minnesota showing major Precambrian divisions and the location of Figure 2B.

B. Precambrian geologic setting of Sherburne County and surrounding region. Letters designate distinct intrusions within the East-Central Minnesota Batholith (pink): A—Ann Lake pluton; F—Freedhem Granodiorite; G—Glendorado pluton; I—Isle and Warman granites; L—Little Rock pluton; P—Pease pluton; R—Reformatory granodiorite; S—St. Cloud Granite; V—Rockville Granite; and W—Watab diorite. Other intrusions associated with the batholith have not been named. Modified from Jirsa and others (2003).

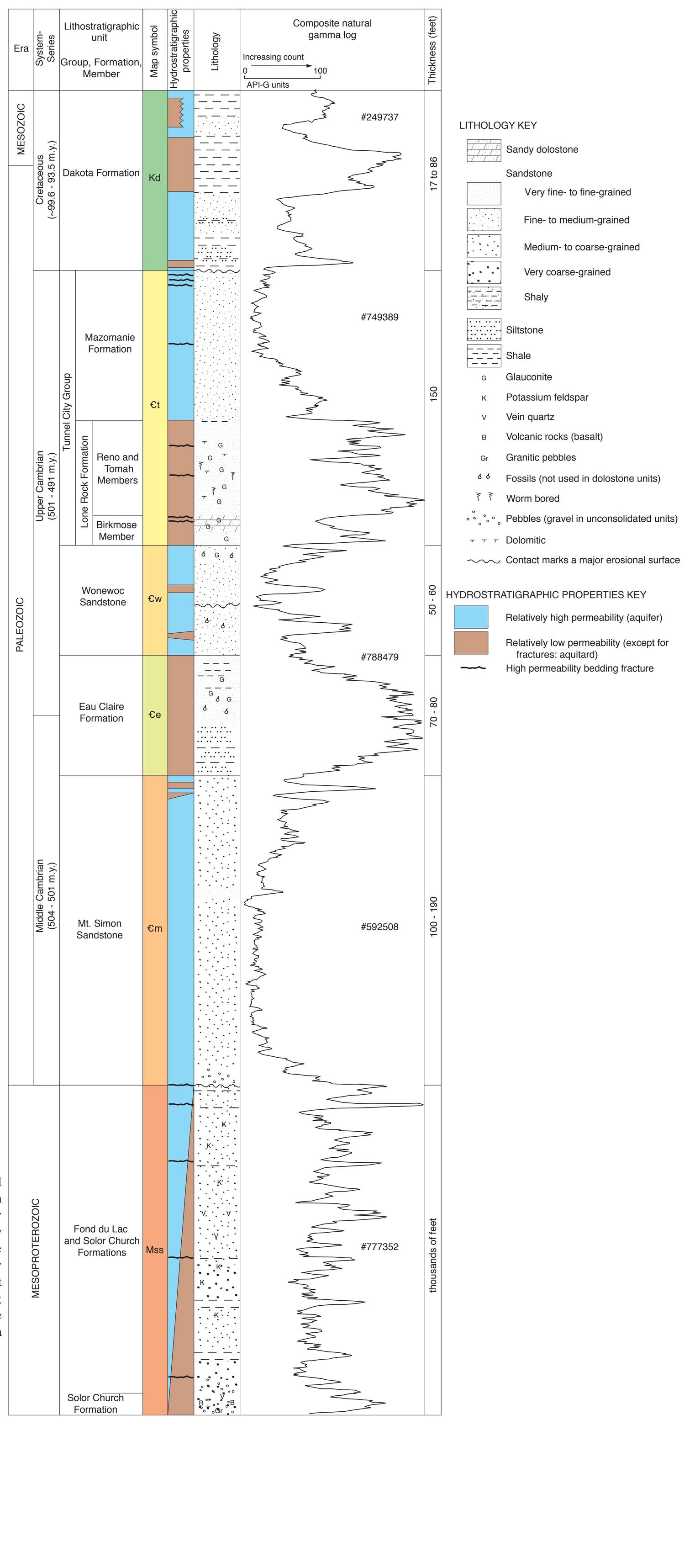


Figure 3. Stratigraphic column showing the age, lithology, thickness, vertical succession, and hydrostratigraphic properties of Mesoproterozoic, Paleozoic, and Mesozoic bedrock units shown on the map. The gamma log is a compilation of four borehole geophysical logs collected from water wells in Sherburne County (unique numbers 77352, 592508, 788479, and 749389) and an exploratory borehole from Wright County (unique number 249737). Natural gamma radiation increases toward the right on the logs. Higher gamma radiation values indicate a high potassium content that is due mostly to high potassium feldspar and clay mineral (mostly illite) content that generally occurs in rocks that have a high content of finer-grained silt- and clay-sized material. Rocks with little potassium bearing fine-grained detrital matter such as dolostone and medium- to coarse-grained quartzose sandstone have comparatively low gamma readings. Many rock formations can be distinguished on a gamma log based on their unique signature.

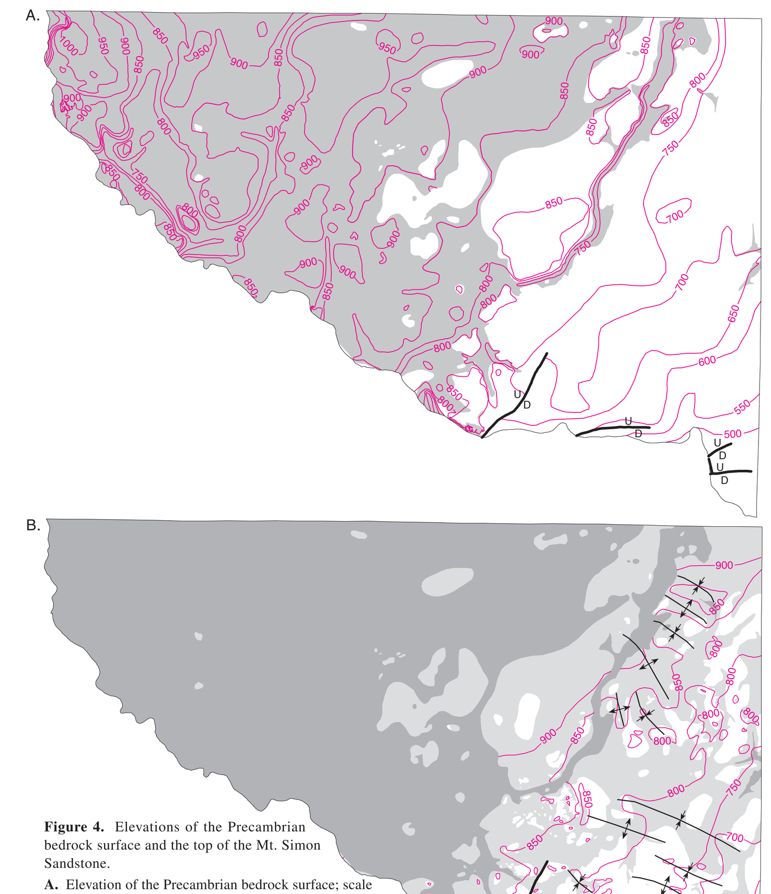


Figure 4. Elevations of the Precambrian bedrock surface and the top of the Mt. Simon Sandstone.

A. Elevation of the Precambrian bedrock surface; scale 1:400,000. Contour interval is 50 feet (15 meters). Map is shaded where the Precambrian surface underlies Quaternary materials and is not overlain by Paleozoic rocks.

B. Elevation of the top of the Mt. Simon Sandstone. Contours are 50 feet (15 meters) and are inferred in areas where the Mt. Simon Sandstone is partly eroded (light gray). Areas where the Mt. Simon Sandstone is entirely eroded are dark gray.

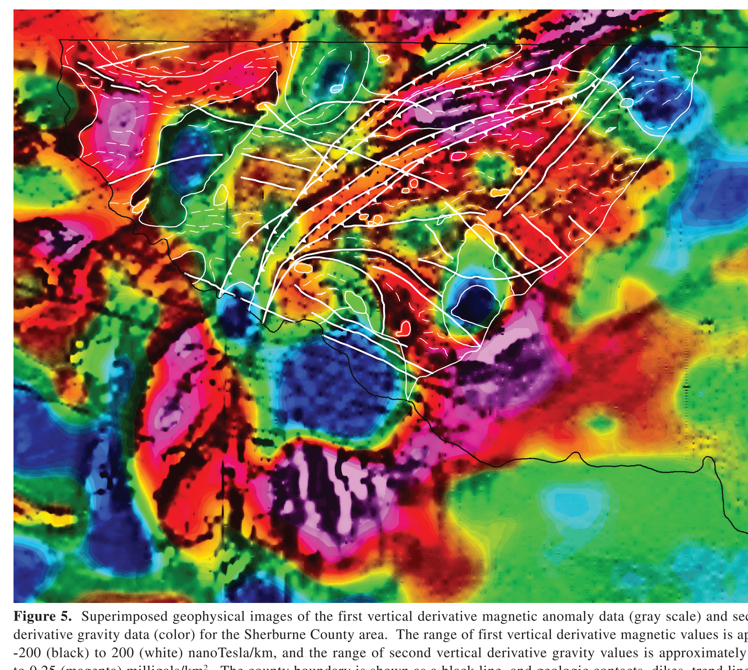


Figure 5. Superimposed geophysical images of the first vertical derivative magnetic anomaly data (gray scale) and second vertical derivative gravity data (color) for the Sherburne County area. The range of first vertical derivative magnetic values is approximately -200 (black) to 200 (white) nanoTesla/km, and the range of second vertical derivative gravity values is approximately -0.25 (blue) to 0.25 (magenta) milligals/km^2. The county boundary is shown as a black line, and geologic contacts, dikes, trend lines, and faults (Precambrian rocks only) are shown by white lines. Scale is 1:400,000. General relationships among rock properties, anomaly signatures, and rock type can be used to help map bedrock geology. For example, low-density, non-magnetic rocks, such as the Foley granite, are characterized by low second vertical derivative gravity values and a subdued first vertical derivative magnetic signature. On the other hand, moderately dense and strongly magnetic rocks, such as the Reformatory granodiorite, are characterized by pronounced highs in the second vertical derivative gravity data and first vertical derivative magnetic data. Such relationships were used in conjunction with existing information from outcrops and drill holes to produce the bedrock geologic map. Note that the anomalies are continuous beneath unit Mss, but become increasingly subdued to the south and east due to increased thickness of the sedimentary cover.

INTRODUCTION

Sherburne County is almost completely covered by Quaternary glacial till, lacustrine sand, outwash deposits, terrace deposits, swamp deposits (peat), and floodplain alluvium (Meyer and Hobbs, 1993). However, there are a few outcrops of Precambrian (Mesoproterozoic, Paleoproterozoic, and Archean) rocks in the northwestern part of the county—mostly Reformatory granodiorite. Paleozoic and Mesozoic rocks are entirely covered by Quaternary and recent deposits. The thickness of unconsolidated Quaternary and recent deposits ranges from less than 50 feet (15 meters) to more than 400 feet (122 meters; see Plate 6, *Bedrock topography* and *Depth to Bedrock* for the thickness variation in unconsolidated deposits).

Mapping of the Precambrian rocks relies heavily on geophysical data, specifically gravity and magnetic data. The Precambrian geology shown here represents a minor revision of that shown on the recently published state map of bedrock geology (Jirsa and others, 2011), which in turn was revised from an earlier map of this area by Jirsa and others (2003). The earlier mapping relied on drill hole and geophysical data existing at the time, as well as 40 core holes drilled in Sherburne County and adjacent areas to specifically test geophysical interpretations (Jirsa and Chandler, 1997). The revisions integrated on the current map and cross-section (Fig. 1) are based on newly reprocessed geophysical data (Chandler, 2007; Chandler and others, 2008), new geophysical models (Fig. 1), new drilling of rotary-sonic core holes by the Minnesota Geological Survey (see Plate 3, *Surficial Geology*), and recently compiled water well records. Recently published radiometric dates, relying on either U-Pb analyses of zircons or $^{40}Ar/^{39}Ar$ analyses of biotite and hornblende, have greatly improved our interpretation of Precambrian geology in the region (Holm and others, 2005; Van Schmus and others, 2007), and those dates pertinent to Sherburne County are given in the Description of Map Units.

Mapping of Paleozoic and Mesozoic rocks is based on data from water wells, observation wells, engineering borings, including drillers' and engineers' logs, geophysical logs, and geologists' descriptions of well cuttings and rock cores.

GENERAL GEOLOGY

The Precambrian geology of Sherburne County encompasses Archean (~3,100 million years ago [Ma]) to Mesoproterozoic (~1,100 Ma) time, but it is heavily influenced by the Paleoproterozoic Penokean (~1,850 Ma) and Yavapai (~1,780 Ma) orogenies. These two plate-convergent events were associated with extensive accretion and magmatism, through which a considerable amount of crustal materials were added to the southern margin of the Archean Superior craton (Fig. 2). During the Penokean orogeny, northwest-verging thrusting of Archean and Paleoproterozoic rocks formed a series of fault-bounded slivers of rock (referred to as "panels" by Chandler and others, 2007; Fig. 2B) that were tectonically stacked and metamorphosed (Southwick and Morey, 1991; Jirsa and others, 2003). In a plate-tectonic context the Paleoproterozoic metasedimentary and metavolcanic rocks within the Princeton panel in central Sherburne County (Fig. 2B) might represent accreted island arc rocks, and the Archean granitic gneiss and schist of the Becker panel (Fig. 2B) might represent an exotic fragment of Archean crust that collided and accreted with the Superior craton at the culmination of the Penokean orogeny (Chandler and others, 2007).

The western part of Sherburne County is underlain by a series of granitic intrusions that were emplaced approximately 1,780 Ma, subsequent to Penokean orogenesis, and are part of what is known collectively as the East-Central Minnesota Batholith (Fig. 2B; Holm and others, 2005). Granitic magmas of the batholith are interpreted to have been emplaced at mesocrustal levels (9 to 13 miles [15 to 21 kilometers] deep; Holm and others, 2007) during an episode of post-orogenic heating in a crust that was over-thickened by compression during the Penokean orogeny (Holm and others, 2005; Chandler and others, 2007). In a plate-tectonic model, Holm and others (2005) proposed that the emplacement of the East-Central Minnesota Batholith and related rocks may have coincided with a reversal from south-dipping (Penokean) to north-dipping (Yavapai) subduction at about 1,800 Ma, after which slab roll-back to the southeast may have caused an overall reduction of compressive stress. This, combined with possible softening associated with post-orogenic heating and magmatism, may have ultimately resulted in the collapse of the over-thickened Penokean crust. Pre-existing Penokean thrust faults may have controlled the development of crustal wedges that were extruded from beneath the collapsing orogenic lid (Schneider and others, 2004; Holm and others, 2007). In this model the Becker and Princeton terranes represent remnants of the upper-crustal orogenic lid, whereas the East-Central Minnesota Batholith and adjacent rocks to the north, including the McGrath Gneiss, Sartell Gneiss, Hillman Tonalite, and Little Falls Formation, represent exhumed mesocrustal rocks (Fig. 2B). Accordingly, the Malmo structural discontinuity (Fig. 2B) represents the footwall fault of the exhumed mesocrustal crust.

One of the largest intrusions of the East-Central Minnesota Batholith is the Reformatory granodiorite (Fig. 2B, unit Ꝑgd), which has type-exposures at quarries near and within the Minnesota Correctional Facility—St. Cloud (formerly the Minnesota State Reformatory For Men) in the extreme northwestern part of Sherburne County. Several scattered exposures of the Reformatory granodiorite lie immediately to the east and northeast of the reformatory outcrops, and one exposure of the Foley granite (unit Ꝑgr) lies near the northern boundary of the county. Field relations observed in Benton County to the north (Jirsa and Chandler, 2010) indicate that the Foley granite represents a relatively younger phase of the East-Central Minnesota Batholith than the Reformatory granodiorite, a relationship that is consistent with U-Pb age dates (Holm and others, 2005). On the basis of scattered drill hole data and geophysical expression, the Reformatory granodiorite is inferred to extend eastwards from the outcrop areas to central Sherburne County. Geophysical signatures indicate that granites similar to the Foley granite have intruded the Reformatory granodiorite to the east. Magnetic granodioritic rocks of the Glendorado pluton (Fig. 2B) are inferred to extend into extreme north-central Sherburne County. Various granitic plutons within the Princeton and Becker terranes are inferred to be related in some way to the East-Central Minnesota Batholith, but no geochronologic and little geologic data are currently available to support this.

A narrow subcrop of Mesoproterozoic sedimentary rocks of the Keweenawan Supergroup (unit Mss) extends north from Wright County into south-central Sherburne County, where it forms the bedrock surface between the younger Paleozoic rocks to the east and the older Precambrian rocks to the west (Steenberg and Chandler, 2012). In east-central Sherburne County these Mesoproterozoic sedimentary rocks also occur at the bedrock surface, along the floor of a paleo-valley that cuts through the Paleozoic strata (see Plate 6, *Bedrock Topography* and *Depth to Bedrock*). The Mesoproterozoic sedimentary rocks, which accumulated during the development of the Midcontinent Rift, thicken eastwards from a feather-edge near the eastern margin of Paleozoic rocks to thousands of feet beneath the southeastern part of the county (Fig. 1). The rift formed during a thermo-tectonic event 900 to 1,200 million years ago that involved extension of the earth's crust with concurrent faulting, volcanism, plutonism, and later deposition of a thick sequence of sedimentary rocks (Chandler and others, 1989). The distribution of these rocks is poorly known in Sherburne County because they are represented only by a few drill cuttings and gamma logs. They likely correlate with parts of the Hinckley Sandstone, and Fond du Lac and Solar Church Formations.

Parts of the Precambrian bedrock in Sherburne County (as elsewhere in Minnesota) are covered with scattered and discontinuous patches of clayey material called saprolite. Saprolite formed by intense chemical weathering of bedrock over a period of millions of years. The weathering process altered some crystalline components, especially feldspar, to kaolinite (Parham, 1970). Saprolite sections intersected by drill holes have thicknesses ranging from a few feet to over 120 feet (35 meters). Despite conversion of crystalline minerals to clay during the weathering process, saprolite commonly retains some of the chemical composition and rock fabric, which can be used to determine original rock type and structural attributes. The saprolite may have been continuous over the region until it was partially removed by glaciation and other types of erosion (Patterson and Boerboom, 1999).

Paleozoic and Mesozoic rocks are represented by the Middle to Upper Cambrian Mt. Simon Sandstone and Eau Claire Formation, the Upper Cambrian Wonewoc Sandstone and Tunnel City Group, and the Upper Cretaceous Dakota Formation (Fig. 3). The Paleozoic rocks were deposited in shallow marine seas in a topographic depression, the Hollandale embayment, that formed on top of the earlier formed Midcontinent Rift during the early part of the Paleozoic era. Sandstone and shale dominate these formations in Sherburne County, carbonates occur only as relatively thin layers in them. The Precambrian bedrock surface and the upper surfaces of the Paleozoic formations slope to the east and south toward the axis of the Hollandale embayment (Fig. 4). A sequence of sedimentary rocks as much as 1,500 feet (457 meters) thick of Middle Cambrian to Devonian age is preserved along the axis of the Minnesota part of the embayment along the Minnesota–Iowa border. In Sherburne County, only the basal few hundred feet of this sequence of sedimentary rocks remains because the upper parts were eroded, mostly prior to and during Quaternary glaciations. The Cretaceous Dakota Formation was deposited in a fluvially dominated delta plain on the eastern margin of the Western Interior Seaway that covered the western interior of North America during the later part of the Mesozoic era. It is much more extensive toward the south and southwest in Minnesota, and only scattered erosional remnants remain in western Sherburne County (Setterholm, 1990).

DESCRIPTION OF AEROMAGNETIC AND GRAVITY DATA AND INTERPRETIVE PROCEDURES

Mapping of the Precambrian bedrock beneath Sherburne County relies significantly on indirect examination using gravity data, which are sensitive to density variations in the bedrock, and magnetic data, which are sensitive to magnetic variations in the bedrock. The density and magnetic variations are quite pronounced for many bedrock units in east-central Minnesota (Chandler and others, 2008), making gravity and magnetic data especially effective tools for geologic mapping in areas such as Sherburne County, where most of the Precambrian rocks are overlain by thick cover.

The gravity data are from a statewide compilation (Chandler and Schaap, 1991), and in Sherburne County are based on ground stations taken roughly 1 mile (1.6 kilometers) apart. The reduced data (Bouguer anomaly) for the Sherburne County area were gridded at a 0.3-mile (0.5-kilometer) interval, and the data were enhanced for geologic mapping by computing the second vertical derivative of the Bouguer anomaly data. To mitigate the effects of minor errors, the derivative data were slightly smoothed by upward continuing to 1.2 miles (2 kilometers) above the surface.

The aeromagnetic (airborne magnetic) data were acquired as part of a statewide survey program (Chandler, 1991), and in Sherburne County the data were acquired using north–south flight lines, which were flown 1,312 to 1,640 feet (400 to 500 meters) apart and 492 to 656 feet (150 to 200 meters) above the ground. The aeromagnetic grid used here was derived from a recently composited, 328-foot (100-meter) grid of the state (Chandler and others, 2008), where individual data sets had been analytically continued to a common level of 492 feet (150 meters) above the ground. The gridded aeromagnetic data were reduced to vertical polarization (reduce to pole), which corrects for the inclination of the earth's magnetic field, thereby placing anomalies more directly above their sources. To further enhance the aeromagnetic data for geologic mapping, the first and second vertical derivatives of the anomaly data were calculated.

The utility of gravity and magnetic data for mapping Precambrian geology is demonstrated in Figure 5, which shows interpreted contacts, dikes, and faults superimposed on combined images of the second vertical derivative of the gravity data (color) and the first vertical derivative of the magnetic data (gray scale).

GEOLOGIC CROSS SECTION

The geologic structure of the Precambrian rocks that are shown on cross section A–A' (Fig. 1, lower) are based largely on modeling of gravity and magnetic anomaly data. Modeling was along a profile assuming two-dimensional (strike-infinite) sources, although some end corrections were allowed for finite-strike sources. To assure reliable modeling up to the margins of Sherburne County, the original model profiles extended slightly beyond the ends of the cross section shown on the bedrock map. During the iterative matching of model signatures to observed signatures, cross-adjustments were made between the models and the geologic map of the bedrock surface. Constrained by density and magnetic susceptibility values derived from rocks from east-central Minnesota (Chandler and others, 2008), the model studies indicated that the anomaly sources in Sherburne County may extend down to 14,110 to 18,045 feet (4,300 to 5,500 meters) below the surface, and most contacts and faults are interpreted to dip steeply to vertical. Steep southeastward dips are indicated for the thrusted metasedimentary and metavolcanic sequences that make up the Princeton terrane, which are consistent with northwestward vergence during the Penokean orogeny. Mesoproterozoic sedimentary rocks associated with the Midcontinent Rift System are interpreted to lap gently onto the southeastern end of profile A–A', and they are interpreted to reach a maximum thickness of 7,550 feet (2,300 meters) at the eastern county boundary.

Most of the intermediate intrusive rocks (unit Ꝑgd) are interpreted to have densities of 2,720 to 2,800 kg/m^3 and magnetic susceptibilities of 0.01131 to 0.04142 SI. Most of the felsic intrusive rocks (unit Ꝑgr) are interpreted to have densities of 2,670 to 2,720 kg/m^3 and magnetic susceptibilities of 0.0 to 0.01882 SI. The metamorphosed volcanic and sedimentary rocks of the Princeton terrane are interpreted to have densities of 2,720 to 2,750 kg/m^3 and magnetic susceptibilities of 0.01005 to 0.03644 SI, which are consistent with intermediate volcanic rocks. The Archean gneissic rocks are interpreted to be fairly heterogeneous, with densities of 2,700 to 2,780 kg/m^3 and magnetic susceptibilities of 0.0 to 0.03770 SI. The Mesoproterozoic sedimentary rocks associated with the Midcontinent Rift System are interpreted to have the lowest density along the profile, 2,450 kg/m^3, and to be non-magnetic.

Below the sources described above, the crust is assumed to consist of rock with an intermediate density of 2,750 kg/m^3 and high magnetic susceptibility (0.01885 SI), which would be consistent with an intermediate rock such as granodiorite. Similar interpretations have been advanced in the area previously to accommodate regional scale magnetic anomaly signatures (Chandler and others, 2007, 2008), but such interpretations remain somewhat speculative. In the case of this cross section, this deeper layer had only a minor effect on the modeled magnetic signature.

HYDROSTRATIGRAPHIC PROPERTIES OF BEDROCK

Stratified sedimentary bedrock is a significant source for ground water in Sherburne County, especially around the city centers of Big Lake and Elk River. This map and associated diagrams provide information about the distribution of these units. The important hydrostratigraphic properties are permeability (the ability to transmit water) and porosity (the capability to store water). The hydrostratigraphic column in Figure 3 distinguishes layers that have relatively high permeability (easily transmitting water) versus layers that have lower permeability (relatively more difficult to transmit water). High permeability layers are potential aquifers, able to store and yield water in usable amounts. The low permeability layers are potential aquitards or confining layers that retard flow and separate aquifer layers from one another in many places. The following generalizations are based upon a report by Runkel and others (2003).

In Sherburne County, the most important aquifer is the coarse-grained sandstone of the Mt. Simon Sandstone. Other important aquifers are the sandstone of the Mazomanie Formation and the Wonewoc Sandstone. The Lone Rock and Eau Claire Formations are important aquitards that are composed principally of fine-grained sandstone, siltstone, and shale. However, units that are considered to be aquifers may locally contain low permeability layers that serve as aquitards, such as the upper part of the Mt. Simon Sandstone. Aquitards that have a very low permeability in a vertical direction commonly contain horizontal bedding planes and fractures that are conductive enough to yield large amounts of water, particularly where they are at or near the bedrock surface. Horizontal as well as vertical fractures are more common in bedrock layers that are at or near the bedrock surface and unconfined by overlying strata. Aquitards under such conditions have a diminished ability to retard the flow of water to underlying aquifers.

The Mesoproterozoic sedimentary rocks contain layers of medium- to coarse-grained sandstone that are important aquifers in parts of Sherburne County, though the quartz cementation in the Hinckley Sandstone may diminish its permeability and usefulness. The Solor Church Formation is finer-grained than the overlying Hinckley Sandstone and Fond du Lac Formation.

Fractures in Precambrian crystalline rocks and sandy zones in the saprolite provide the source of water for wells in western Sherburne County.

MINERALIZATION POTENTIAL OF THE PRECAMBRIAN ROCKS

Parts of Sherburne County have a slightly elevated potential for volcanogenic massive sulfide deposits. Chandler and others (2008) hypothesized that the metavolcanic rocks of the Milaca and Princeton panels (Fig. 2B) may correlate with those of the Wisconsin magmatic terranes to the east, which are associated with several known volcanic massive sulfide deposits (Dematties, 1989, 1994). Factors favoring volcanic massive sulfide exploration in Sherburne County include the occurrence of saprolite, which raises the possibility of supergene enrichment, and a generally thin cover of glacial deposits in the central and western parts of the county (see Plate 6, *Bedrock topography* and *Depth to Bedrock* for the thickness variation in unconsolidated deposits), which would accommodate geophysical exploration using electromagnetic methods. In addition some potential exists for the Precambrian rocks regarding aggregate and dimension stone, especially in the vicinity of the outcrop areas in northwestern Sherburne County.

DESCRIPTION OF MAP UNITS

MESOZOIC ROCKS

Kd **Dakota Formation (Upper Cretaceous)**—Primarily claystone with minor sandstone. Known only from drillers' logs in Sherburne County, it is similar to the Dakota Formation described from core and cuttings in Wright County to the south (Steenberg and Chandler, 2012). Unit consists of dark gray to brown, non-calcareous claystone. The equivalent claystones in Wright County contain shells of articulated calcareous bivalves, pelecypods, black lignite plant fragments, and siderite concretions (Steenberg and Chandler, 2012). This unit overlies saprolite and Precambrian crystalline rock units. The Dakota Formation is lithically similar to mudstone, siltstones, and sandstones in Brown and Nicollet Counties that contain an assemblage of palynomorphs with pollen taxa that are no older than Late Cretaceous (Late Cenomanian) in age (Hu and others, 2008).

PALEOZOIC ROCKS

Nomenclature has been revised for some Paleozoic formations in Minnesota (Mossler, 2008) and some formation names formerly in use at the Minnesota Geological Survey have been replaced by names widely accepted elsewhere in the region. Rocks formerly included in the Franconia Formation are now assigned to the Tunnel City Group, which is subdivided into the Mazomanie Formation and the Lone Rock Formation. The Lone Rock Formation includes the three members formerly included in the Franconia Formation: the Reno, Tomah, and Birkmose Members, which were described and named by Berg (1954). The interval formerly referred to as the Ironton-Galesville Sandstone is now named the Wonewoc Sandstone. More detailed discussion of these revisions is given in Mossler (2008).

Ꞓt **Tunnel City Group (Upper Cambrian)**—The Tunnel City Group, formerly named the Franconia Formation (Berg, 1954), ranges from less than 135 to approximately 180 feet (41 to 49 meters) in thickness in the map area and is missing because of erosion over much of the county. It is now divided into two formations: the upper Mazomanie Formation, and the lower Lone Rock Formation (Fig. 1; Mossler, 2008). Both the Mazomanie Formation and the members of the Lone Rock Formation were originally named and described by Berg (1954), who considered all to be members of the Franconia Formation. The uppermost non-glauconitic formation, the Mazomanie Formation, is dominantly white to yellowish-gray, fine- to medium-grained, cross-stratified, generally friable, quartz sandstone. Glauconitic grains typically are absent and never exceed 5 percent (Berg, 1954). Some beds contain brown, intergranular dolomite as cement. The Mazomanie Formation is about 60 to 80 feet (18 to 24 meters) thick. The Lone Rock Formation underlies and intertongues with the Mazomanie Formation. The uppermost member of the Lone Rock Formation is the Reno Member, which is pale yellowish-green, very fine- to fine-grained glauconitic, feldspathic sandstone with thin, greenish-gray shale partings. The sandstone is well sorted and contains thin zones containing dolomitic intraclasts. The Reno Member is underlain by the Tomah Member, a thin unit composed of interbedded, grayish-yellow-green, feldspathic siltstone, very fine-grained sandstone, and pale green shale. The Tomah Member is sparsely glauconitic. The basal Birkmose Member is grayish-yellow-green, fine-grained sandstone that is cemented by dolomite. There are dark red dolostone beds in the upper part of the Birkmose Member. The Birkmose Member is highly glauconitic and contains abundant dolomitic intraclasts. The Lone Rock Formation is about 100 feet thick (30 meters) thick. The basal Birkmose Member is about 20 feet (6 meters) thick and the overlying Tomah Member is less than 10 to 15 feet (3 to 4.5 meters) thick. Most of the Lone Rock Formation in Sherburne County consists of the uppermost Reno Member.

Ꞓw **Wonewoc Sandstone (Upper Cambrian)**—This unit, formerly referred to as the Ironton-Galesville Sandstone, is composed mostly of fine- to coarse-grained, moderately to well sorted, light gray to yellowish-gray, quartz sandstone. The upper part is the coarsest-grained; the lower part is finer-grained, better sorted, and progressively finer-grained toward its base. Thin shale and siltstone beds are present throughout the formation but are more common in the lower part. The very fine-grained sandstone in the lower part is feldspathic. The sandstone contains abundant linguliform brachiopod valves locally along bedding planes. The thickness of the formation is 50 to 60 feet (15 to 18 meters). The Wonewoc Sandstone is conformable with overlying and underlying formations; however, there is a subtle internal unconformity marked by a pebbly sandstone layer observed in outcrop and cores elsewhere (Runkel and others, 1998). However, it is not possible to recognize the unconformity in well cuttings or geophysical logs.

Ꞓe **Eau Claire Formation (Middle and Upper Cambrian)**—The formation is composed of yellowish-gray to pale olive-gray, very fine-grained, feldspathic sandstone, siltstone, and shale. The upper part is predominantly shale and siltstone, the lower part predominantly glauconitic sandstone and siltstone (Mossler, 1992). It contains linguliform brachiopod shells. The formation ranges from 70 to 80 feet (21 to 24 meters) in thickness. The contact with the underlying Mt. Simon Sandstone is conformable and transitional. Siltstone and shale beds of the Eau Claire Formation are commonly interbedded with medium- to coarse-grained quartzose sandstone of the Mt. Simon Sandstone.

Ꞓm **Mt. Simon Sandstone (Middle Cambrian)**—The Mt. Simon Sandstone is pale yellowish-brown to grayish-orange-pink to light gray, medium- to coarse-grained, quartz sandstone that contains interbedded siltstone and very fine-grained, feldspathic sandstone, particularly in its upper half to one third (Mossler, 1992). Linguliform brachiopods are present in the upper part of the formation. There is a thin conglomeratic zone at the base. The Mt. Simon Sandstone generally is from 100 to 190 feet (30 to 58 meters) thick in the county. It is unconformable on Mesoproterozoic and older rocks.

MESOPROTEROZOIC ROCKS

Keweenawan Supergroup

Mss **Sandstone, siltstone, and minor shale of the Keweenawan Supergroup—May include the Hinckley Sandstone and the Fond du Lac and Solor Church Formations, undifferentiated**—The uppermost Hinckley Sandstone is salmon colored, quartz-rich, very fine- to medium-grained, quartzose, and moderately- to well-sorted with variable quartz cement. Red-brown shale and siltstone are present in the lower part of the formation. The medial Fond du Lac Formation is moderate reddish-orange to moderate yellow-brown feldspathic sandstone, siltstone, and shale. Its sandstone is poorly sorted with grains that tend to be subrounded to subangular (Morey, 1977; Boerboom, 2001). The combined thicknesses of the Hinckley Sandstone and Fond du Lac Formation are thousands of feet; however, the Hinckley Sandstone is only a small fraction of that thickness. The Solor Church Formation is interbedded sandstone, siltstone, and shale that generally is moderate red to pale reddish-brown (sandstone and siltstone) to dark reddish-brown (mudstone) in color, although dark to light greenish-gray beds occur at depth (Morey, 1977). It is generally poorly to moderately sorted sandstone with grains that are angular to subrounded. It can be carbonate rich, especially in its upper part. The rock is mineralogically immature with appreciable amounts of feldspar grains and volcanic rock fragments (Morey, 1977). The Solor Church Formation is thousands of feet thick, similar to the Fond du Lac Formation; however, its thickness is extremely variable because of faulting of the Mesoproterozoic rocks. It is underlain by volcanics, primarily basalt.

PALEOPROTEROZOIC OR MESOPROTEROZOIC ROCKS

ꝐMn ꝐMr **Diabasic and gabbroic dike**—Northwest- and east–northeast-trending, variably magnetic dikes inferred largely from magnetic anomalies: ꝐMn—normal magnetic polarity; ꝐMr—reversed magnetic polarity. Where exposed in outcrop and sampled from drill core, the rocks are very fine- to medium-grained, subophitic, olivine diabase. May represent several generations of emplacement.

Ꝑmi **Mafic and ultramafic intrusion**—Irregularly shaped plug- and dike-like plutons inferred from small aeromagnetic anomalies. Drilling elsewhere in central Minnesota indicates a variety of lithologies, including serpentinized peridotite, pyroxenite, hornblendite, and hornblende- and mica-bearing diorite and gabbro (Jirsa and others, 2006). One intrusion in Morrison County to the north yielded an Ar-Ar age of 1,791 ± 8 Ma (Holm and others, 2005).

Ꝑgr **Granitic intrusion**—The Foley granite and other granitic units that are inferred to be similar on the basis of shared geophysical attributes, specifically a negative gravity expression and a generally subdued magnetic signature. The Foley granite is a pink to salmon-colored, biotite- and hornblende-bearing granite, medium- to coarse-grained. Shallow dipping trachytoid fabric occurs locally; may be locally intruded by small dikes of granite porphyry and aplite. Essentially non-magnetic, but magnetic phases can exist along contacts with adjacent units. The Foley granite has a U-Pb age of 1,779 ± 4 Ma (Holm and others, 2005).

Ꝑgd **Reformatory granodiorite**—Light gray, hornblende biotite granodiorite, medium- to coarse-grained; displays moderately well-developed trachytoid foliation and local autoliths of more mafic composition. Magnetic and density signatures are moderate. Unit has a U-Pb age of 1,783 ± 11 Ma (Holm and others, 2005). Locally cut by east-trending granitic dikes and larger masses referred to as the St. Cloud Granite.

Ꝑgm **Glendorado pluton**—Granodiorite; based on two drill cores, the rock is pink, white, and black, coarse-grained, and contains biotite and steeply lineated hornblende (Jirsa and Chandler, 1997). Variably magnetic and moderately dense. Unit has a U-Pb age of 1,788 ± 4 Ma (Holm and others, 2005).

Ꝑgu **Granitoid rock, undifferentiated**—Inferred from geophysical signatures to be of low density and commonly magnetic.

Ꝑsm **Schist of primarily sedimentary protolith**—May also include minor volcanic, volcaniclastic, and sheared granitic rock; metamorphosed locally to greenschist facies.

Ꝑmv **Schist of primarily volcanic protolith**—May also include minor components of metasedimentary rocks. Dark-colored rocks are metamorphosed locally to greenschist facies; unit typically has positive gravity and magnetic signatures.

ARCHEAN

Agn **Quartzofeldspathic orthogneiss**—Forms the major component of the Becker panel. May locally include granitic rocks and variably deformed and metamorphosed Paleoproterozoic rocks. Drill core samples from hole T-101 has yielded a U-Pb age of approximately 2,800 Ma and a Sm/Nd model age of 3,180 Ma (Van Schmus and others, 2007).

REFERENCES

Berg, R.R., 1954, Franconia Formation of Minnesota and Wisconsin: Geological Society of America Bulletin, v. 66, p. 857-882.

Boerboom, T.J., 2001, Bedrock geologic map and sections, pl. 2 *of* Boerboom, T.J., project manager, Geologic atlas of Pine County, Minnesota: Minnesota Geological Survey County Atlas C-13, 7 pls., scale 1:100,000.

Chandler, V.W., 1991, Aeromagnetic map of Minnesota: Minnesota Geological Survey State Map S-17, scale 1:500,000.

———2007, Upgrade of aeromagnetic databases and processing systems at the Minnesota Geological Survey: Minnesota Geological Survey Open-File Report 07-6.

Chandler, V.W., Jirsa, M.A., and Boerboom, T.J., 2007, Penokean tectonics along a promontory-embayment margin in east-central Minnesota: Precambrian Research, v. 157, p. 26-49.

———2008, A gravity and magnetic investigation of east-central Minnesota: Insights into the structure and evolution of the Paleoproterozoic Penokean Orogen: Minnesota Geological Survey Report of Investigations 66, 33 p

Chandler, V.W., McSwiggen, P.L., Morey, G.B., Hinze, W.J., and Anderson, R.R., 1989, Interpretation of seismic reflection, gravity, and magnetic data across Middle Proterozoic Mid-Continent Rift System, northwestern Wisconsin, eastern Minnesota, and central Iowa: American Association of Petroleum Geologists Bulletin, v. 73, p. 261-275.

Chandler, V.W., and Schaap, B.D., 1991, Bouguer gravity anomaly map of Minnesota: Minnesota Geological Survey State Map S-16, scale 1:500,000.

Dematties, T.A., 1989, A proposed geologic framework for massive sulfide deposits in the Wisconsin Penokean volcanic belt: Economic Geology, v. 84, p. 946-952.

———1994, Early Proterozoic volcanogenic massive sulfide deposits in Wisconsin: An overview: Economic Geology, v. 89, no. 5, p. 1122-1151.

Holm, D.K., Schneider, D.A., Rose, S., Mancuso, C., McKenzie, M., Foland, K.A., and Hodges, K.V., 2007, Proterozoic metamorphism and cooling in the southern Lake Superior region, North America, and its bearing on crustal evolution: Precambrian Research, v. 157, p. 106-126.

Holm, D.K., Van Schmus, W.R., MacNeill, L.C., Boerboom, T.J., Schweitzer, D., and Schneider, D., 2005, U-Pb zircon geochronology of Paleoproterozoic plutons from the northern mid-continent, U.S.A.: Evidence for subduction flip and continent convergence after Geon 18 Penokean orogenesis: Geological Society of America Bulletin, v. 117, no. 3, p. 259-275.

Hu, S., Jarzen, D.M., and Dilcher, D.L., 2008, New species of angiosperm pollen from the Dakota formation (Cenomanian, Upper Cretaceous) of Minnesota, U.S.A.: Palynology, v. 32, p. 71-79.

Ibs-von Seht, M., and Wohlenberg, J., 1999, Microtremor measurements used to map thickness of soft soil sediments: Bulletin of the Seismological Society of America, v. 89, p. 250-259.

Jirsa, M.A., Boerboom, T.J., Chandler, V.W., Mossler, J.H., Runkel, A.C., and Setterholm, D.R., 2011, Geologic map of Minnesota, bedrock geology: Minnesota Geological Survey State Map S-21, scale 1:500,000.

Jirsa, M.A., and Chandler, V.W., 1997, Scientific test drilling and mapping in east-central Minnesota, 1994-1995: Summary of lithologic results: Minnesota Geological Survey Information Circular 42, 105 p.

———2010, Bedrock geology, pl. 2 *of* Setterholm, D.R., Project manager, Geologic atlas of Benton County, Minnesota: Minnesota Geological Survey County Atlas C-23, scale 1:100,000.

Jirsa, M.A., Chandler, V.W., Lively, R.S., and Boerboom, T.J., 2003, Maps of bedrock geology and superimposed magnetic on gravity (SMOG) anomaly for east-central Minnesota: Minnesota Geological Survey Miscellaneous Map M-132, scale 1:200,000.

Jirsa, M.A., Miller, J.D., Jr., Severson, M.J., and Chandler, V.W., 2006, Final report on the geology, geochemistry, geophysical attributes, and platinum group element potential of mafic to ultramafic intrusions in Minnesota, excluding the Duluth Complex: Minnesota Geological Survey Open-File Report 06-3, 49 p.

Lane, J.W., Jr., White, E.A., Steele, G.V., and Cannia, J.C., 2008, Estimation of bedrock depth using the horizontal-to-vertical (H/V) ambient-noise seismic method: Symposium on the Application of Geophysics to Engineering and Environmental Problems, Proceedings of the Environmental and Engineering Geophysical Society, 13 p.

Meyer, G.N., and Hobbs, H.C., 1993, Quaternary geologic map of Sherburne County, Minnesota: Minnesota Geological Survey Miscellaneous Map M-77, scale 1:100,000.

Morey, G.B., 1977, Revised Keweenawan subsurface stratigraphy, southeastern Minnesota: Minnesota Geological Survey Report of Investigations 16, 67 p.

Mossler, J.H., 1992, Sedimentary rocks of Dresbachian age (Late Cambrian), Hollandale embayment, southeastern Minnesota: Minnesota Geological Survey Report of Investigations 40, 71 p.

———2008, Paleozoic stratigraphic nomenclature for Minnesota: Minnesota Geological Survey Report of Investigations 65, 76 p., 1 pl.

Nakamura, Y., 1989, A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface: Quarterly Report Railway Technical Research Institute, v. 30, no. 1, p. 25-30.

Nogoshi, M., and Igarashi, T., 1971, On the amplitude characteristics of microtremor (pt. 2; in Japanese with English abstract): Journal of the Seismological Society of Japan, v. 24, p. 26-40.

Parham, W.E., 1970, Clay mineralogy and geology of Minnesota's kaolin clays: Minnesota Geological Survey Special Publication SP-10, 142 p.

Parolai, S., Bormann, P., and Milkert, C., 2002, New relationships between Vs, thickness of sediments, and resonance frequency calculated by the H/V ratio of seismic noise for Cologne Area (Germany): Bulletin of the Seismological Society of America, v. 92, p. 2521-2527.

Patterson, C.J., and Boerboom, T.J., 1999, The significance of pre-existing, deeply weathered crystalline rock in interpreting the effects of glaciation in the Minnesota River valley, USA: Annals of glaciology, v. 28, p. 53-58.

Runkel, A.C., McKay, R.M., and Palmer, A.R., 1998, Origin of a classic cratonic sheet sandstone: Stratigraphy across the Sauk II-Sauk III boundary in the upper Mississippi valley: Geological Society of America Bulletin, v. 110, p. 188-210.

Runkel, A.C., Tipping, R.G., Alexander, E.C., Jr., Green, J.A., Mossler, J.H., and Alexander, S.C., 2003, Hydrogeology of the Paleozoic bedrock in southeastern Minnesota: Minnesota Geological Survey Report of Investigations 61, 105 p., 2 pls.

Schneider, D., Holm, D.K., Boyle, C.O., Hamilton, M., Jercinovic, M., 2004, Paleoproterozoic development of a gneiss dome corridor in the southern Lake Superior region, U.S.A., *in* Whitney, D.L., Tesseyier, C., and Siddoway, C.S., eds., Gneiss domes in orogeny: Geological Society of America Special Paper 380, p. 339-357.

SESAME, 2004, Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations: Measurements, processing and interpretation: WP12 European commission—Research general directorate project no. EVG1-CT-2000-0026 SESAME, report D23.12, 62 p.

Setterholm, D.R., 1990, Geologic maps of the Late Cretaceous rocks, southwestern Minnesota: Minnesota Geological Survey Miscellaneous Map M-69, 2 pls., scale 1:750,000.

Steenberg, J.R., and Chandler, V.W., 2012, Bedrock geology, pl. 2 *of* Tipping, R.G., project manager, Geologic atlas of Wright County, Minnesota: Minnesota Geological Survey County Atlas C-30, 6 pls., scale 1:100,000.

Southwick, D.L., and Morey, G.B., 1991, Tectonic imbrication and foredeep development in the Penokean orogen, east-central Minnesota—An interpretation based on regional geophysics and the results of test-drilling: U.S. Geological Survey Bulletin 1904-C, p. C1-C17.

Van Schmus, W.R., Schneider, D.A., Holm, D.K., Dodson, S., and Nelson, B.K., 2007, New insights into the southern margin of the Archean-Proterozoic boundary in the north-central United States based on U-Pb, Sm-Nd, and Ar-Ar geochronology: Precambrian Research, v. 157, p. 80-105.

The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government. This map is submitted for publication with the understanding that the U.S. Government is authorized to reproduce and distribute reprints for governmental use. Supported by the U.S. Geological Survey, National Cooperative Geologic Mapping Program, under assistance Award No. G11AC20222.