University of Minnesota
MINNESOTA GEOLOGICAL SURVEY
Harvey Thorleifson, Director

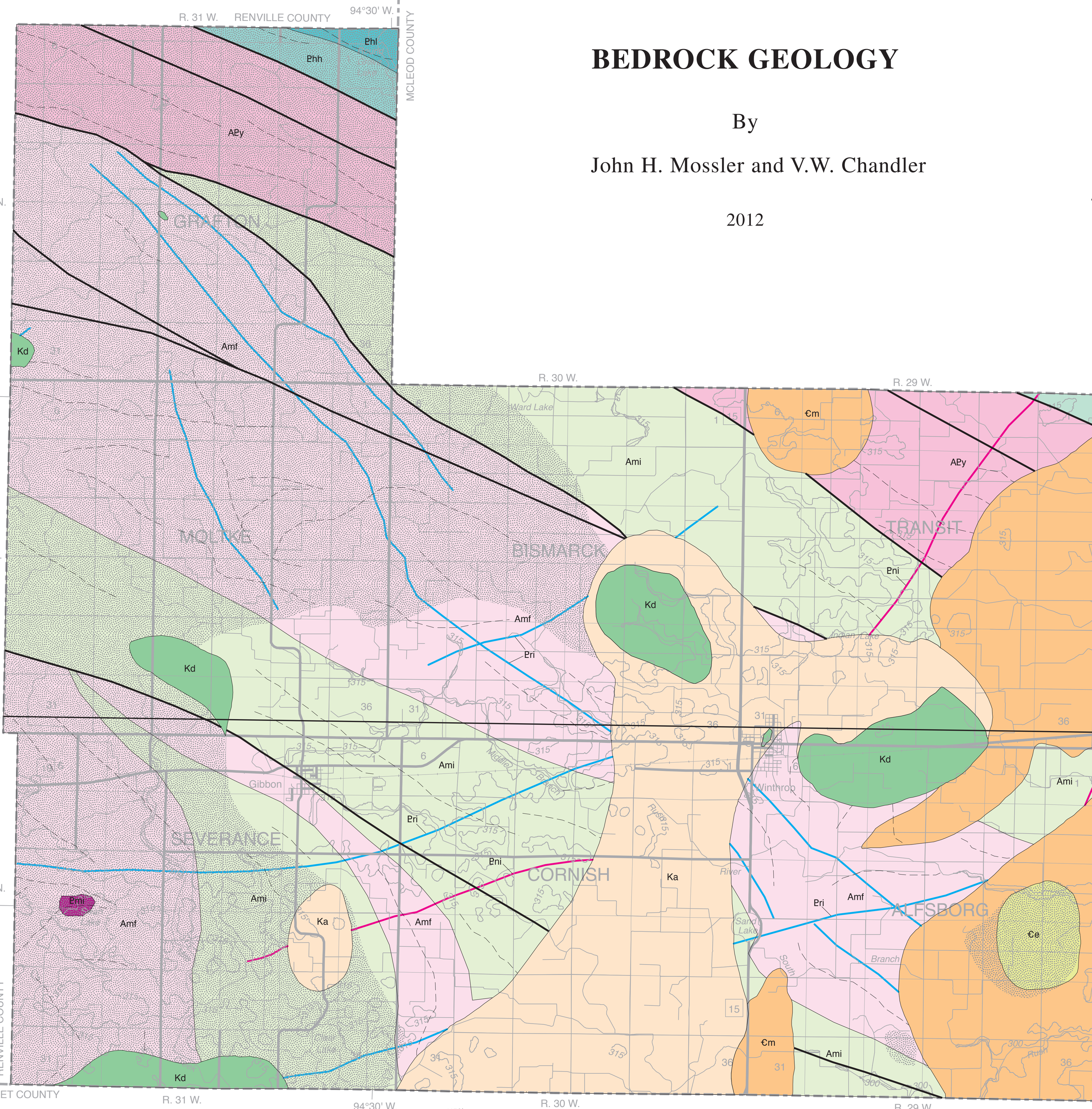
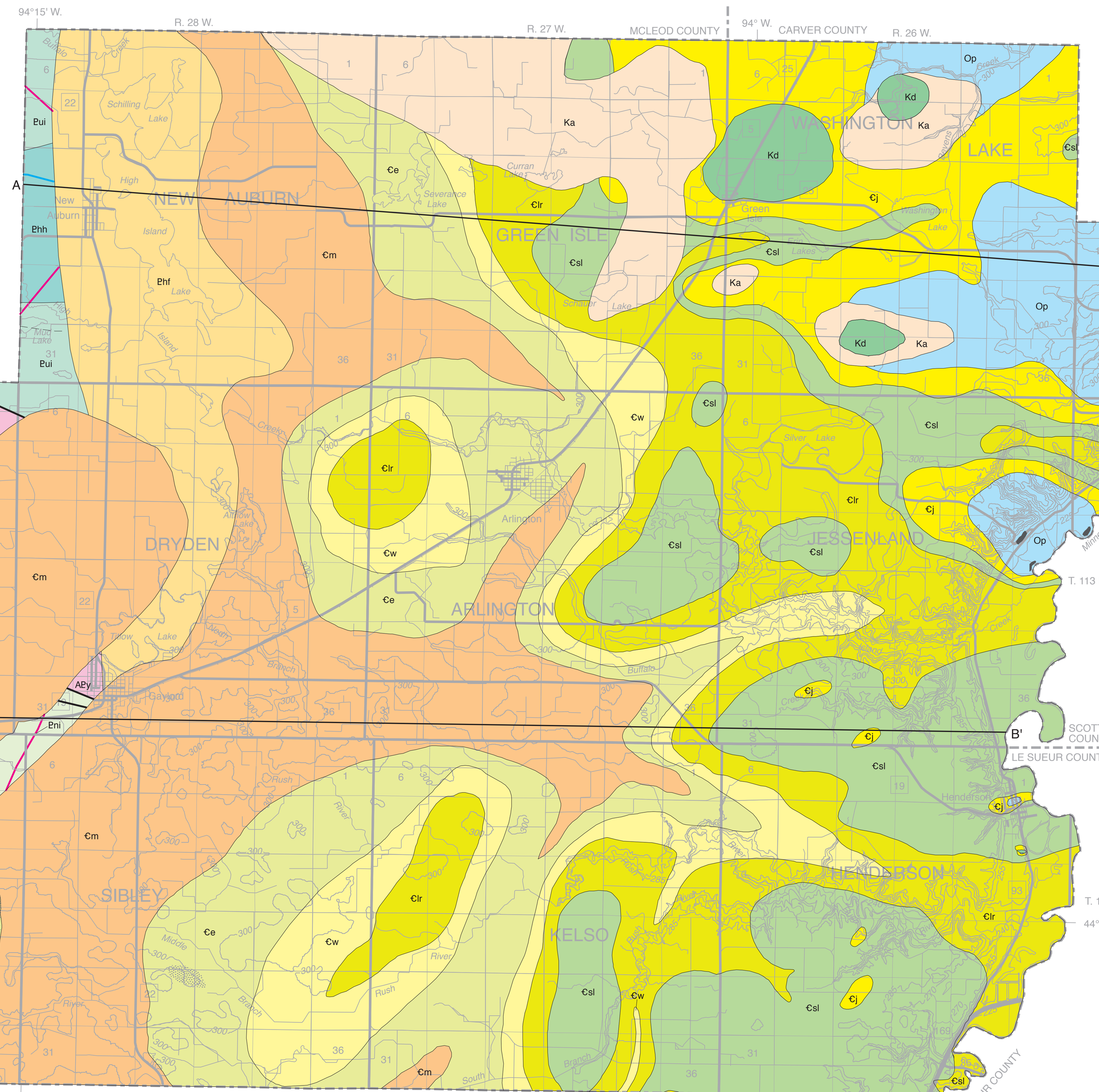
Prepared and Published with the Support of
THE U.S. GEOLOGICAL SURVEY AS PART OF THE 2009 STATE GEOLOGIC MAPPING PROGRAM ELEMENT (STATEMAP) OF THE NATIONAL COOPERATIVE GEOLOGIC MAPPING PROGRAM, THE SIBLEY COUNTY BOARD OF COMMISSIONERS, AND THE MINNESOTA ENVIRONMENT AND NATURAL RESOURCES TRUST FUND AS RECOMMENDED BY THE LEGISLATIVE-CITIZEN COMMISSION ON MINNESOTA RESOURCES

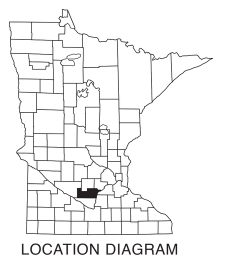
BEDROCK GEOLOGY

By

John H. Mossler and V.W. Chandler

2012

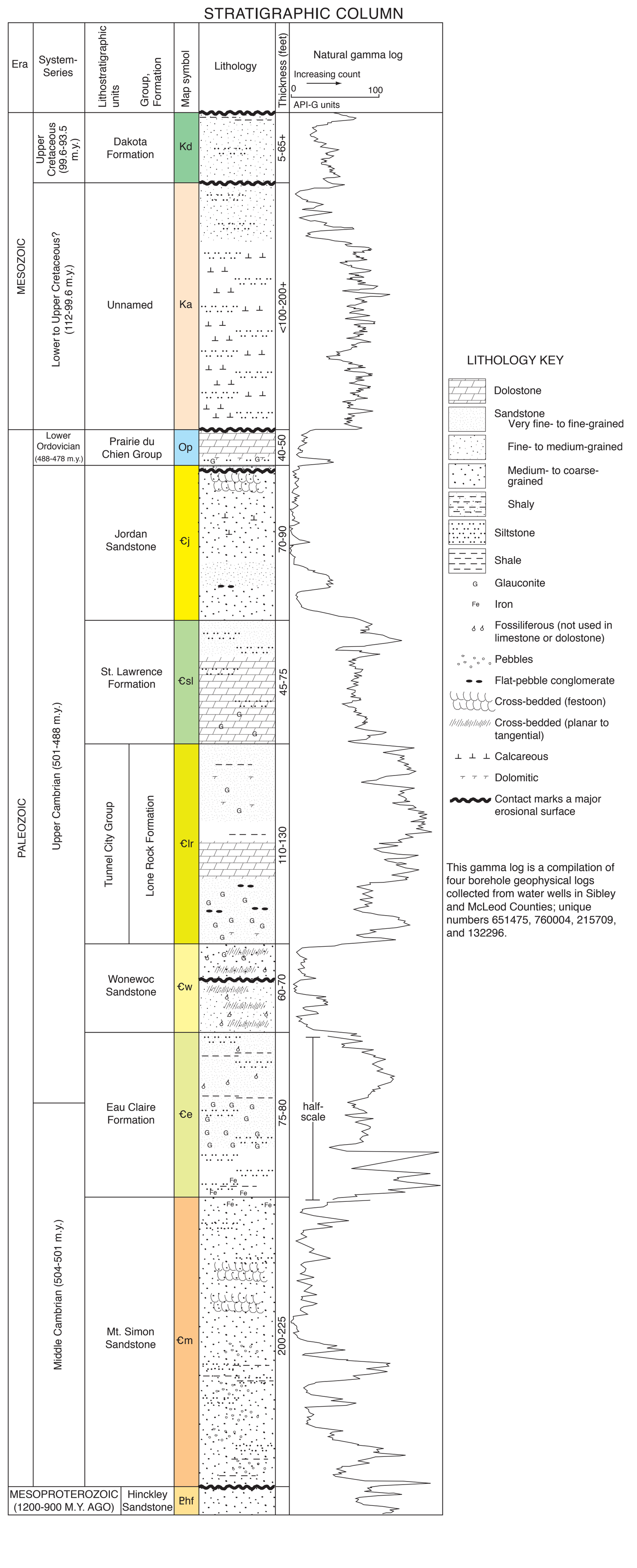


Digital base modified from 1990 Census TIGER/Line Files of U.S. Bureau of the Census (source scale 1:100,000); county border files modified from Minnesota Department of Transportation files; digital base annotation by Minnesota Geological Survey.
Universal Transverse Mercator Projection, grid zone 15
1983 North American Datum
GIS compilation by R.S. Lively
Edited by Lori Robinson

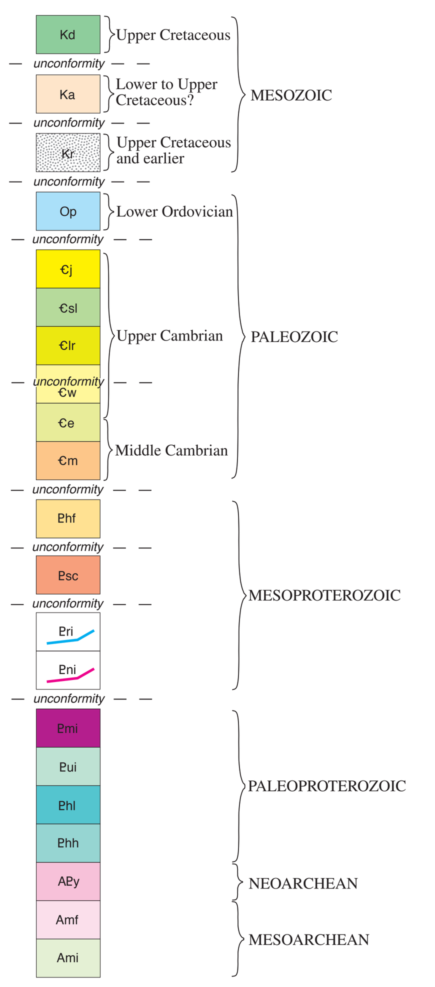
APPROXIMATE MEAN DECLINATION, 2010

SCALE 1:100 000

CONTOUR INTERVAL 15 METERS



CORRELATION OF MAP UNITS



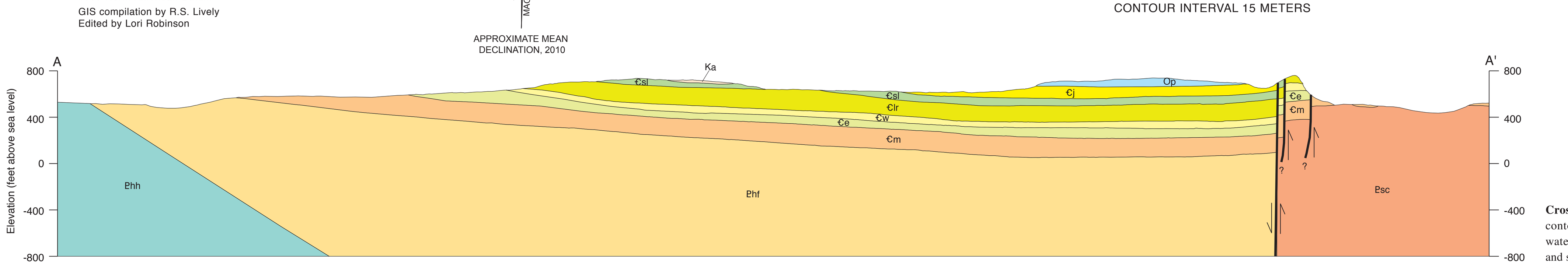
MAP SYMBOLS

Geologic contact—Approximately located.

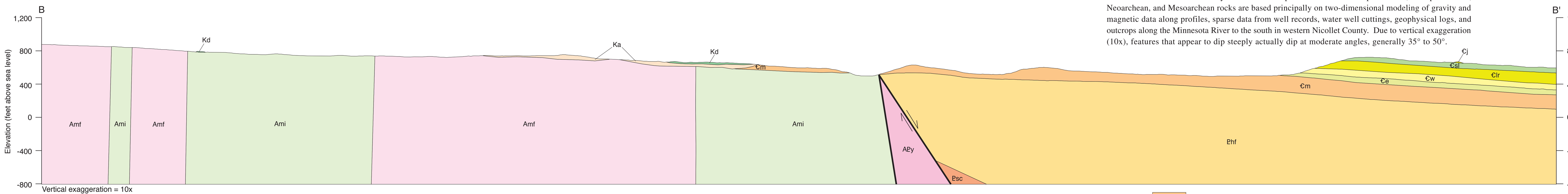
Fault—Faults in Paleozoic rocks are interpreted to be dip-slip. Letters indicate what is inferred to be the most recent relative vertical displacement: U, up; D, down. Faults are concealed by Quaternary sediments and recent alluvium and are inferred from subsurface geologic data supplemented by aeromagnetic and gravity data. Contrasts in magnetic intensity on aeromagnetic maps are inferred to be largely the expression of faults in underlying Proterozoic and Archean rocks. Offsets of overlying Paleozoic strata indicate that some of these faults were rejuvenated during and after Early Paleozoic time.

Structural form line—Approximate structural fabric in Precambrian rocks based on patterns in derivative-enhanced magnetic data.

Bedrock outcrop—Detailed mapping of bedrock exposure reported by Upham (1888) and Sloan and Danes (1962).



Cross sections—The contact between glacial deposits and bedrock is based on bedrock topography contours shown on the map. Contacts for Paleozoic and Mesozoic units are based on drillers' logs, water well cuttings, geophysical logs, and outcrops along the Minnesota River in the eastern and south-central Nicollet County. Contacts and dips of contacts for Mesoproterozoic, Paleoproterozoic, Neoarchean, and Mesoarchean rocks are based principally on two-dimensional modeling of gravity and magnetic data along profiles, sparse data from well records, water well cuttings, geophysical logs, and outcrops along the Minnesota River to the south in western Nicollet County. Due to vertical exaggeration (10x), features that appear to dip steeply actually dip at moderate angles, generally 35° to 50°.



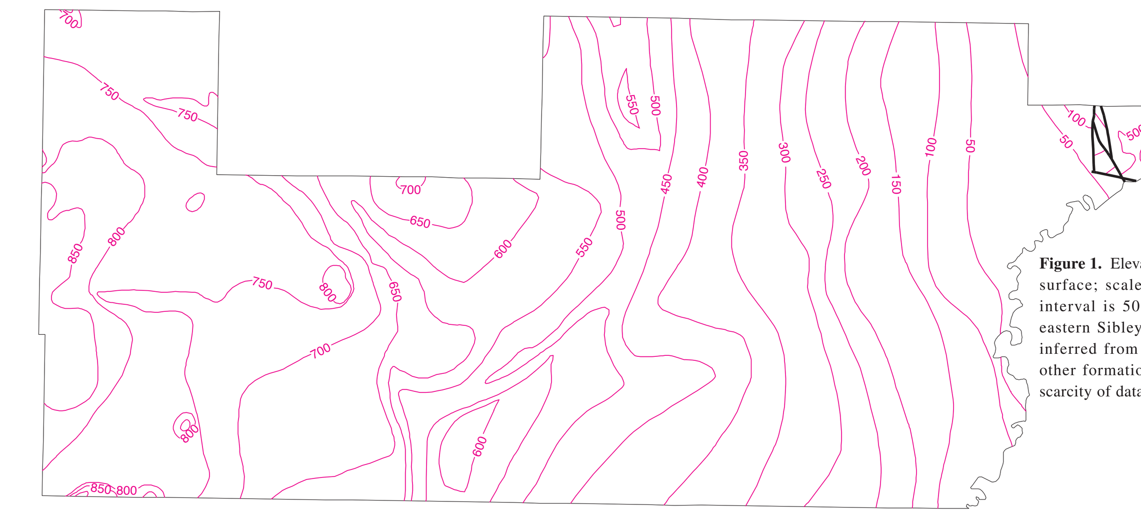


Figure 1. Elevation of the Precambrian surface; scale 1:300,000. Contour interval is 50 feet (15 meters). In eastern Sibley County, contours are inferred from vertical projection of other formation contacts because of scarcity of data.

INTRODUCTION

This geologic map and cross sections depict the bedrock formations exposed at the land surface or lying beneath Quaternary deposits of variable thickness in Sibley County. This map shows how the bedrock would appear if it were viewed from an aerial perspective after all the overlying unconsolidated material was stripped away. Quaternary glacial till, lake sediments, outwash, and river alluvium cover the bedrock across most of the county. The unconsolidated deposits reach a maximum thickness of more than 500 feet (152 meters) and bedrock exposures are limited to a few reported in the eastern part of the county, along the Minnesota River (Upham, 1888; Sloan and Danes, 1962). Therefore, bedrock geology must be generalized from available water well and geophysical data. The production of this map and cross sections relied on information from a number of sources, including water-well and scientific drilling records (including holes drilled for this project as well as holes drilled by the Minnesota Department of Natural Resources for their observation well network), outcrop descriptions from previous investigators, geophysical surveys, and previous geologic mapping of Sibley and adjacent counties, particularly mapping for the state bedrock geology map (Jirsa and others, 2011; see Plate 1, *Data-Base Map* for the distribution of data). Some seismic data were collected specifically for this STATEMAP project by the Minnesota Department of Natural Resources (Todd Petersen) and the Minnesota Geological Survey (V.W. Chandler). Aeromagnetic and gravity data were particularly useful for mapping Precambrian rocks in the region, which are associated with strong contrasts in density and magnetization (Chandler and others, 2008).

There are several different kinds of bedrock mapped in Sibley County: Archean gneiss and granite, Neoarchean and/or Paleoproterozoic mylonitic rock, Paleoproterozoic mafic and intermediate rocks in plugs and dikes, Paleoproterozoic granite and granodiorite, Mesoproterozoic sedimentary rocks, and Paleozoic and Mesozoic sedimentary rocks.

Prominent buried bedrock valleys to the north in McLeod County and south in Nicollet County join valley systems that cross Sibley County (see Plate 6, *Bedrock Topography* and *Depth to Bedrock*). These valleys apparently drain toward the east through valleys that cross northwestern LeSueur County and western Scott County into southern Carver County. Areas underlain by the Prairie du Chien Group (Op) and St. Lawrence Formation (Ꞓsl) in eastern and central Sibley County form topographically high areas on the bedrock surface because they are more resistant to erosion than the other rock formations (cross sections A–A', B–B').

Buried valleys incised into the bedrock surface combined with the east to southeasterly regional dip of the Paleozoic bedrock are the primary influences on the map distribution of bedrock geologic units. In eastern Sibley County, the principal units of the bedrock surface are Paleozoic units that become progressively older from east to west. In western Sibley County, the Paleozoic units have been stripped away and the principal rock formations are Precambrian gneiss and granite. A narrow subcrop of Mesoproterozoic sedimentary rock (unit Ꝑhf) extends south from McLeod County into north-central Sibley County, where it forms the bedrock surface beneath the Quaternary sediments between Precambrian gneiss and granite and the Paleozoic rocks. The Mesoproterozoic sedimentary rocks thicken eastwards beneath the Paleozoic formations to thousands of feet (cross sections A–A', B–B'). Soft Mt. Simon Sandstone underlies major buried bedrock valleys.

The Cretaceous sedimentary rocks (units Kd and Ka) were probably laid down across this eroded bedrock surface as a continuous blanket, but subsequent erosion has separated them into scattered, discontinuous outliers.

Paleozoic rocks near the northeastern edge of the county are displaced by faults that appear to be the result of reactivation of Mesoproterozoic Midcontinent Rift System faults. The faults in eastern Sibley County caused cumulative displacement of about 400 feet (122 meters) in Paleozoic rock formations, sufficient to juxtapose two different formations along the fault contact. Blocks of bedrock that have dropped down alongside faults preserve remnants of relatively young formations, such as the Prairie du Chien Group, and uplifted blocks locally have bedrock as old as Mesoproterozoic age lying directly beneath unconsolidated Quaternary deposits (cross section A–A'). To the west of the faults, in east-central Sibley County, the Paleozoic rocks are folded in a broad syncline.

DESCRIPTION OF MAP UNITS

MESOZOIC ROCKS

Mesozoic rocks occur as thin layers of sandstone, siltstone, carbonate, and shale that were deposited in shallow seas and marginal marine environments during the Cretaceous period about 90 million years ago (Fig. 1; Setterholm, 1990; Toth 1996). There is a weathering residuum or saprolith (unit Kr) that mantles most of the Archean and Paleoproterozoic rocks that is interpreted to have formed during early Late Cretaceous time and earlier (Parham, 1970).

Kd **Dakota Formation (Upper Cretaceous)**—The unit is very fine- to medium-grained, light gray to light brown, quartzose sandstone that is clayey. The sandstone generally is friable but has variable cementation by iron oxide and calcite. It differs from Paleozoic quartz sandstone in that the grains are commonly subangular to angular. The sandstone contains dark gray to black lignitic material and some thin beds of gray and pale red siltstone and light green shale. The sandstone contains thin layers of quartz and chert conglomerate at its base.

Mapped distribution of Cretaceous rocks is more speculative than for other map units; prediction of their subsurface distribution is rendered difficult by the presence of profound unconformities bounding these strata, and because information from water well records alone is generally inadequate to confidently identify the strata as distinct from light colored Quaternary sand bodies or from in situ residuum developed on Precambrian or Phanerozoic rocks. Local occurrences of yellow, gray, and white shale and sandstone are mapped as Late Cretaceous in age in places where drilling records indicate the composition of underlying bedrock and their elevation and stratigraphic position makes them unlikely to be in situ weathering residuum or Paleozoic bedrock. Strata can be more confidently assigned to the Cretaceous period if there are cuttings available for examination, as there were at several of the occurrences in Sibley County.

The Late Cretaceous sedimentary rocks occur as erosional remnants that unconformably overlie older Phanerozoic formations (Humphrey, 1958) and Precambrian granitic rocks, typically at elevations between about 750 and 880 feet (228 to 268 meters). They reach a maximum thickness of over 65 feet (20 meters) in Sibley County.

Strata to the south along the Minnesota River in western Nicollet County from the Courtland area and west can be assigned to the Cretaceous period with more confidence compared to the patchy strata classified as Cretaceous age farther east and north in Sibley and Nicollet Counties. Palynological studies from a clay pit near Courtland in western Nicollet County (Hu and others, 2008), outcrops in Brown County near New Ulm, and at a clay pit near Fort Ridgely in extreme western Nicollet County (Pierce, 1961) indicate a Late Cretaceous age for the unit. There, an upper shale unit is interpreted to be the Woodbury Member of the Dakota Formation and the lower sandy unit is interpreted to be the Nishnabotna Member of the Dakota Formation (Toth, 1996).

Ka **Unnamed formation (Lower to Upper Cretaceous?)**—This unit is yellow-gray to pale olive and light gray-green and pale red-brown sandstone, siltstone, and shale. The sandstone generally is very fine- to medium-grained quartz. The unit is calcareous and contains thin beds of limestone, and calcite cement and concretions (Austin, 1970). The red colors are found primarily in the lower part of the unit. The unit is thickest in western Sibley County near the Nicollet County border, where it reaches 130 feet (40 meters), and in northeastern Sibley County on the McLeod County border, where it is more than 200 feet (61 meters) thick; however, more commonly it is less than 100 feet (30 meters) in thickness. Distinguishing this unit from weathered, fine-grained Paleozoic rocks and from the saprolith on top of the Precambrian granitic rocks can be difficult on drillers' logs and makes mapping this unit difficult, particularly where the saprolith and this unit overlie Precambrian crystalline rocks in close juxtaposition. The formation unconformably overlies the Precambrian crystalline rocks and Paleozoic formations ranging in age from Middle to Late Cambrian and possibly Ordovician. This unit does not crop out in Sibley County, but exposures in neighboring Nicollet County along the Minnesota River and small tributary streams from Courtland to near New Ulm were described by Austin (1970), who considered them to be Late Cretaceous in age and to postdate the saprolith. The unit has not produced biostratigraphically useful fossils but lithically appears similar to McLeod County strata to the north that contain gymnospermous pollen and dinoflagellate cysts that indicate a possible Early to Late Cretaceous age (Ravn, 2009, unpub. data).

Kr **Saprolith (Upper Cretaceous and older)**—White to light gray to greenish-gray or red, kaolinitic clay and sandy claystone derived primarily from the weathering of Precambrian granitic and gneissic rocks. Where it overlies granite or gneiss, it grades down from highly altered saprolith into less altered material, then to fresh parent material. Material altered from granitic rock generally contains abundant medium- to coarse-grained, angular quartz sand grains. The upper part of the saprolith has commonly been reworked by water into beds of sand and sandy clay capped by hard white to purple, red, or black pisolitic clay where the entire unit has been preserved (Parham, 1970). Organic-rich clay in this reworked interval in Renville County to the west contains pollen of Late Cretaceous age (John Hall, 1969, unpub. data in Parham, 1970, p. 9). The saprolith is most extensive in the western part of the county where it overlies granitic bedrock; eastward, where it overlies Paleozoic sedimentary rocks, it generally occupies cavities in karsted carbonate rocks. The saprolith is over 75 feet (23 meters) thick in a test hole drilled in Bismarck Township in western Sibley County, but thickness variations are poorly constrained elsewhere because the unit is not an aquifer and most drillers stop near the top of the unit.

PALEOZOIC ROCKS

Paleozoic rocks in Minnesota occur as thin layers of sandstone, siltstone, dolostone, and shale that were deposited in shallow seas and marginal marine environments from 504 to 478 million years ago (Runkel and others, 2007; Mossler, 2008).

Nomenclature has been revised for some Paleozoic formations in Minnesota, and some formation names formerly in use at the Minnesota Geological Survey have been replaced by names widely accepted elsewhere in the region (Mossler, 2008). 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 interval formerly referred to as the Ironton and Galesville Sandstones is now named the Wonewoc Sandstone. More detailed discussion of these revisions is given in Mossler (2008).

Op **Prairie du Chien Group, undivided (Lower Ordovician)**—Predominantly light brown to grayish-orange; thin- to thick-bedded dolostone. It commonly contains small, unfilled vugs. Meter-scale microbial mounds are common. The dolostone is sandy, glauconitic, and contains some shale stringers near its base. Most of this dolostone is equivalent to the Hager City Member of the Oneota Dolomite of the Prairie du Chien Group of southeastern Minnesota. However, a faunule discovered in an outcrop in Jessenland Township (T. 113 N., R. 26 W., sec. 13, NW) is interpreted to represent the Shakopee Formation (Sloan and Danes, 1962). Large (meter-scale), solution enhanced vertical joints and bedding plane fractures are particularly common in the Hager City Member where it is exposed in Nicollet and Blue Earth Counties to the south. In Nicollet County, in exposures along the north bank of the Minnesota River (T. 108 N., R. 27 W., secs. 11, 14) and nearby areas, these features are most commonly filled with gray to white shale and siltstone that appears to be lithically similar to the underlying Blue Earth Member siltstone bed and may be siltstone that was squeezed up into solution cavities.

The Blue Earth Member of the Oneota Dolomite of the Prairie du Chien Group is a thin, dolomitic siltstone below the dolostone of the Hager City Member. It is feldspathic and contains glauconite (Humphrey, 1958). It is equivalent to the upper part of the Coon Valley Member of the Oneota Dolomite of southeastern Minnesota (Mossler, 2008). The Blue Earth Member is about 3 feet (1 meter) thick in outcrop.

A thin interval of medium- to coarse-grained quartzose sandstone from a few inches to 6.5 feet (2 meters) thick that disconformably overlies the Jordan Sandstone (Ꞓj) and conformably underlies the Blue Earth Member to the south in Nicollet and LeSueur Counties contains an Ordovician-age fauna (Powell, 1935). It is considered to be a basal part of the Oneota Dolomite, equivalent to the lower part of the Coon Valley Member of the Oneota Dolomite of southeastern Minnesota (Runkel, 1994a; Runkel and others, 1999). Powell (1935) and Stauffer and Thiel (1941) referred to this sandstone as the Kasota Sandstone because the Ordovician-age fauna it contained was substantially younger than the fauna in the Jordan Sandstone. However, its lithic similarity to the Jordan Sandstone makes it impractical to map as a unit separate from the Jordan Sandstone despite the presence of a regional unconformity between them.

The Hager City Member is mined extensively for building-stone and aggregate products across the Minnesota River to the south in Blue Earth County.

The Prairie du Chien Group is up to 40 to 50 feet (12 to 15 meters) thick in Sibley County, much thinner than the maximum unerroded thicknesses observed elsewhere in southern Minnesota. The unit is present in the eastern part of the county, mostly as highly dissected, isolated, erosional remnants near the Minnesota River.

Ꞓj **Jordan Sandstone (Upper Cambrian)**—Dominantly light gray sandstone with minor siltstone and shale; includes two interlayered facies (Runkel, 1994b) that are not separated on the map. They are medium- to coarse-grained, trough to planar cross-stratified, generally friable quartz sandstone; and very fine-grained, feldspathic sandstone that is commonly bioturbated or has hummocky cross stratification. Lenses of siltstone and shale are present in the fine-grained facies. The major part of the very fine-grained facies forms a regionally continuous interval that gradationally overlies the St. Lawrence Formation (Ꞓsl), although there are lithologically similar intervals intercalated with the medium- to coarse-grained facies at higher stratigraphic intervals. Exposures in Nicollet County to the south, along the Minnesota River west of Mankato, and to the northeast in Scott County, have extensive silica cementation. The formation is from 70 to 90 feet (21 to 27 meters) thick where the entire unit is preserved; however, it is highly dissected by erosion throughout most of its occurrence in Sibley County. It is present in the subsurface in eastern Sibley County at Henderson and Green Isle. It is most extensive in the subsurface of Faxon and Washington Lake Townships in northeastern Sibley County. The Jordan Sandstone is not known to crop out in Sibley County, but it crops out extensively to the south in Nicollet County in the bluffs along the Minnesota River immediately to the west of North Mankato, along Seven Mile Creek, and in the banks of the Minnesota River south of St. Peter. The Jordan Sandstone is mined in LeSueur County to the southeast for silica sand that is used in various products including frac sand in the oil and gas industry. It also crops out at Carver Rapids to the north in Carver County, and to the east in Scott County, where it was formerly mined for industrial sand.

Ꞓsl **St. Lawrence Formation (Upper Cambrian)**—Most of the formation is yellowish-gray to grayish-orange-pink to pale red, dense to finely crystalline, silty dolostone. There is light greenish-gray to pale red, dolomitic siltstone in the uppermost part.

The St. Lawrence Formation generally is 45 to 75 feet (14 to 23 meters) thick where it is undissected by erosion. It is abnormally thin at Green Isle, where it consists of only 26 feet (8 meters) of pale red sandy siltstone. It subcrops extensively throughout eastern Sibley County. It is eroded in the western part of the county.

Glauconite content in the dolostone increases toward the base of the formation. The contact of the St. Lawrence Formation with the underlying Lone Rock Formation (unit Ꞓlr) is conformable. It is characterized by a 3 to 7 feet (1 to 2 meters) thick zone of interbedded glauconitic, intraclastic dolostone, and sandstone.

The dolostone beds in the St. Lawrence Formation exposed to the south along the Minnesota River in Nicollet County commonly have solution features typical of karstic carbonate rock.

Ꞓlr **Lone Rock Formation (Upper Cambrian)**—Sandstone, shale, and dolostone. The sandstone is yellowish-gray to gray-yellow-green to light olive-gray, very fine- to fine-grained, silty, feldspathic, and glauconitic. It generally is friable and poorly cemented but has some dolomite cement and interlocking feldspar overgrowths. Interbedded, thin, grayish-green shale partings are common. There is minor pale green siltstone. Dolostone beds are thin to medium-thick, pink-orange-gray to pale red, commonly intraclastic, and most abundant in the lower one-half to one-third of the formation. The basal 35 to 40 feet (11 to 12 meters) is sandier; it is glauconitic, friable or poorly cemented, and generally fine-grained, though it contains some coarser grains. Phosphatic brachiopods are common near the base.

The Lone Rock Formation is 110 to 130 (34 to 40 meters) feet in thickness. It subcrops across the central part of the county and in the bottoms of deep buried valleys in the northeastern part of the county.

Ꞓw **Wonewoc Sandstone (Upper Cambrian)**—Sandstone that is light gray to yellowish-gray, fine- to coarse-grained, moderately to well rounded, and quartzose. Light gray to pale green shale partings are present. Glauconite is present in the upper part of the sandstone and phosphatic brachiopod valves are found throughout the unit. The unit progressively coarsens from its base and is coarsest-grained at the top. Generally friable to moderately cemented. The Wonewoc Sandstone is a maximum of 60 to 70 feet (18 to 21 meters) thick. Contacts with formations above (unit Ꞓlr) and below (unit Ꞓe) are gradational. Regional stratigraphic and paleontological study (Runkel and others, 1998) indicated a regional unconformity occurs within the sandstone that approximates the contact between what were formerly referred to as the Galesville Sandstone and Ironton Sandstone; however, this unconformity generally cannot be distinguished in well cuttings and geophysical logs.

Ꞓe **Eau Claire Formation (Middle to Upper Cambrian)**—Sandstone, siltstone, and shale. The upper part of the Eau Claire Formation is very light gray to yellowish-gray and light brownish-gray, very fine-grained, feldspathic sandstone and siltstone. It is well indurated and cemented by feldspar overgrowths and dolomite. Minor thin beds of pale olive to olive-gray shale and siltstone are interbedded in the sandstone. The unit is very fossiliferous and contains abundant phosphatic brachiopod valves as well as hyolithids and trilobite fragments. The middle part of the Eau Claire Formation is glauconitic, grayish-yellow-green to moderate brown, very fine-grained sandstone and siltstone and grayish-green shale. The basal part is non-glauconitic, yellowish-gray siltstone and grayish-green shale. The lower part has abundant inarticulate brachiopod valves. The contact with the underlying Mt. Simon Sandstone (Ꞓm) commonly is marked by a thin interval of rock with dark red-brown iron oxide stain. The basal contact with the Mt. Simon Sandstone is gradational and contains beds of medium- to coarse-grained sandstone typical of Mt. Simon Sandstone interbedded with the very fine- to fine-grained sandstone of the Eau Claire Formation. The Eau Claire Formation has a maximum thickness of 75 to 85 feet (23 to 26 meters). The basal contact with the Mt. Simon Sandstone is conformable.

Ꞓm **Mt. Simon Sandstone (Middle Cambrian)**—Sandstone with minor thin siltstone and shale beds. The Mt. Simon Sandstone is principally light brown to pale yellowish-brown to grayish-orange-pink, medium- to coarse-grained, quartzose sandstone. There are interbedded, thin layers of pale olive-gray, pale red, or greenish-gray siltstone and silty shale and pale to moderate brown, feldspathic, very fine-grained sandstone that generally are more abundant in the upper part of the sandstone. The upper part has abundant inarticulate brachiopod valves that commonly are goethite-limonite oxids and coated grains near the contact with the Eau Claire Formation. The basal part has more very coarse-grained to granular sandstone beds and commonly is a quartzose conglomerate at the base. The Mt. Simon Sandstone has a maximum thickness of 200 to 225 feet (61 to 69 meters) in Sibley County. The contact of the Mt. Simon Sandstone with Precambrian formations is an unconformity. The Mt. Simon Sandstone overlies Mesoproterozoic sedimentary rocks, principally the Hinckley Sandstone, and the Mesoarchean Morton Gneiss (Southwick, 2002; cross sections A–A', B–B').

MESOPROTEROZOIC ROCKS

Paleozoic bedrock in eastern Sibley County lies on the edge of an eastward-thickening sequence of Mesoproterozoic rocks of the Keweenawan Supergroup that was deposited in the Midcontinent Rift. The rift formed during a thermo-tectonic event 900 to 1,200 million years ago that involved extension of the earth's crust in the area, with concurrent faulting, mafic volcanism, plutonism, and later deposition of a thick sequence of sedimentary rocks (Chandler and others, 1989). Sedimentary rocks of the Midcontinent Rift form the Precambrian surface beneath much of eastern Sibley County, and rift-related igneous rocks are inferred to underlie the extreme eastern part of the county (cross section A–A').

Ꝑhf **Hinckley Sandstone and Fond du Lac Formation**—Sandstone, siltstone, and shale. The Hinckley Sandstone is salmon-colored, very fine- to medium-grained, quartzose sandstone that is variably cemented with quartz. It is moderately to well sorted. Red-brown shale and siltstone are present in the lower part of the formation. The 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 angular (Morey, 1977; Boerboom, 2001). The combined thicknesses of the Fond du Lac Formation and Hinckley Sandstone are thousands of feet; however, the Hinckley Sandstone is only a small fraction of that thickness. The Hinckley Sandstone is a discontinuous unit.

Ꝑsc **Solor Church Formation**—Interbedded sandstone, siltstone, and shale that is generally moderate red or 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. The rock is mineralogically immature with appreciable amounts of feldspar grains and volcanic rock fragments (Morey, 1977). It may be carbonate rich, especially in its upper part. The Solor Church Formation is thousands of feet thick like the Fond du Lac Formation; however, its thickness is extremely variable because of faulting of the Mesoproterozoic rocks. It is underlain by volcanic rocks, primarily basalt.

Ꝑni **West-northwest- and west-southwest-trending dikes**—Negative anomaly signatures in derivative-enhanced magnetic data imply reversed magnetic polarity. These dikes may correlate with similarly polarized dikes described elsewhere, including ca. 1,780 Ma dikes in east-central Minnesota (Boerboom and others, 1995; Jirsa and others, 2003) or 2,067 Ma dikes in southwestern Minnesota (Schmitz and others, 2006).

Ꝑni **Northeast-trending dikes**—Positive magnetic anomaly signatures in derivative-enhanced magnetic data imply normal magnetic polarity. In Nicollet County to the south, northeast-trending dikes appear to intensify to the east, toward the Midcontinent Rift, and they may therefore be related to this feature.

PALEOPROTEROZOIC ROCKS

During Paleoproterozoic time, a ca. 2,100 Ma rifting event and two subsequent convergent events, the ca. 1,850 Penokean Orogeny and the ca. 1,780 Yavapai Orogeny, greatly affected the regions north and east of Sibley County (Holm and others, 2007). The west-northwest-striking, 2,067 ± 1 Ma diabase dikes near Franklin in northeastern Redwood County to the west are generally thought to reflect the rifting event (Schmitz and others, 2006), and some northwest-striking dikes in western Sibley County (see unit Ꝑni) could plausibly reflect this event as well. Some of the metamorphic rocks within units Ꝑhh and Ꝑhl were probably involved in both the Penokean and Yavapai Orogenies. Similarly, some of the intrusive rocks that are inferred beneath Sibley County (units Ꝑui and Ꝑmi) could have been emplaced during either the Penokean or Yavapai Orogenies, although recent geochronologic work implies that Yavapai-age magmatism is dominant in the region (Holm and others, 2007).

Ꝑmi **Plug-like to dike-like plutons of mafic to ultramafic rocks**—Composed of serpentinized peridotite, pyroxenite, hornblendite, and hornblende- and mica-bearing diorite and gabbro. Unit correlates with unit Ꝑgp of Southwick (2002) in southwestern Minnesota. Plutons of this type are typically associated with small, irregular to circular magnetic highs. These plutons may be of Yavapai Orogeny (ca. 1,780 Ma) affinity, although their ages are poorly constrained. Mafic intrusions to the west in Redwood County include the diabase dike near Franklin, which has yielded a Pb-Pb age of 2,067 ± 1 Ma (Schmitz and others, 2006), and the gabbro-pyroxenite of the Cedar Mountain Complex, which has yielded a K-Ar hornblende age of 1,750 Ma (Hanson, 1968).

Ꝑui **Variably magnetic, intermediate-to-felsic intrusive rocks**—Granitoid rocks associated with subdued magnetic and negative gravity signatures. Unit is most likely of Yavapai Orogeny (ca. 1,780 Ma) affinity, although radiometric dates are lacking. This unit may correlate with units Ꝑdt (diorite, tonalite, and gabbro) and/or Ꝑg (granite), as defined by Southwick (2002) in southwestern Minnesota.

Ꝑhl **Hillman-Little Falls panel low-density unit**—Parts of the Hillman-Little Falls panel that are dominated by low-density units, as determined from gravity and magnetic signatures in McLeod County to the north (Chandler and Mossler, 2009). Individual units are not differentiated, but may include those that are equivalent to the felsic phases of the Sartell Gneiss and the Hillman Migmatite, as described in east-central Minnesota (Boerboom and others, 1995; Jirsa and others, 2003; Chandler and others, 2008). Unit may also include significant proportions of ca. 1,780 Ma granitoid intrusions (Holm and others, 2005).

Ꝑhh **Hillman-Little Falls panel dense unit**—Parts of the Hillman-Little Falls panel that are dominated by dense units, as determined from gravity and magnetic signatures in McLeod County to the north (Chandler and Mossler, 2009). Individual units are not differentiated, but may include the Little Falls Formation and denser phases of the Sartell Gneiss and the Hillman Migmatite, as described in east-central Minnesota (Boerboom and others, 1995; Jirsa and others, 2003; Chandler and others, 2008). Unit may also include intermediate to mafic intrusions that are related to the ca. 1,780 East-Central Minnesota Batholith (Holm and others, 2005).

AꝐy **Mylonitic rock associated with the Yellow Medicine shear zone**—This unit correlates with mylonitic unit AꝐy of Southwick (2002) in southwestern Minnesota (no lithologic description given). In Sibley County this unit is characterized primarily by narrow, linear to curvilinear highs in the first vertical derivative and second vertical derivative magnetic data along the southern margin of the Yellow Medicine shear zone.

ARCHEAN ROCKS

Western Sibley County is underlain by rocks that are part of the Archean Minnesota River Valley subprovince of southwestern Minnesota (Southwick, 2002). This subprovince is now thought to have been emplaced by a series of accretionary and igneous events between ca. 3,500 Ma to 2,600 Ma (Bickford and others, 2006), culminating with the emplacement of the Sacred Heart Granite and related intrusions at 2,603 ± 1 Ma to 2,590 ± 1 Ma (Schmitz and others, 2006). The subprovince is divided into separate blocks by prominent shear zones (Southwick, 2002), and one of these, the Yellow Medicine shear zone, crosses through the northwestern and north-central parts of Sibley County. There, a shear zone separates a complex zone of Paleoproterozoic metamorphic and igneous rocks to the north, from the Mesoarchean Morton Gneiss to the south.

Morton Gneiss—As described by Southwick (2002), this rock is generally quartzofeldspathic in composition, and commonly includes tonalitic, granitic, and granodioritic phases, as well as rafts and layers of amphibolite and biotitic gneiss (Grant, 1972). The principal gneissic layering is subhorizontal and folded into broad warps that plunge gently toward the northeast (Southwick, 2002). The Morton Gneiss is generally gray in color. The Morton Gneiss is quarried to the west in Renville County for building stone. Outcrops of the Morton Gneiss and Fort Ridgely Granite are found to the south at the western end of Nicollet County (Lund, 1950). Some domestic water wells in western Sibley County draw water from the granite and/or gneiss.

To the west of Sibley County, granitic, granodioritic, and tonalitic migmatites of the Morton Gneiss have yielded U-Pb ages of 3,422 ± 2 Ma (Schmitz and others, 2006) and 3,524 ± 9 Ma (Bickford and others, 2006), whereas a granodiorite intrusion into the Morton Gneiss has been U-Pb dated at 3,370 ± 8 Ma (Bickford and others, 2006). Detrital zircons in a feldspar-biotite schist overlying the Morton Gneiss to the west in Renville County indicate that it was deposited between 3,140 and 2,600 Ma (Bickford and others, 2006). Granitic phases of the Morton Gneiss that might correlate with the Sacred Heart Granite include an adamellite that yielded a U-Pb age of 2,600 ± 0.4 Ma and an aplite dike that yielded a U-Pb age of 2,590 ± 1 Ma (Schmitz and others, 2006).

Due to scarcity of outcrops, the various units that are described above for the Morton Gneiss are not individually mapped in Sibley County. Instead the Morton Gneiss is coarsely subdivided into felsic and intermediate members, based primarily on gravity and magnetic signatures.

Amf ***Morton Gneiss—felsic composition***—Unit is interpreted to be dominated by felsic rocks, including quartzofeldspathic gneiss and granite, and to be relatively deprived of mafic components, such as tonalitic gneiss and amphibolite rafts. Unit is typically moderately to strongly magnetic, and it commonly is associated with a negative gravity signature. Contacts are inferred from gravity and magnetic data.

Ami ***Morton Gneiss—intermediate to mafic composition***—Unit is interpreted to include a significant proportion of mafic components, such as tonalitic gneiss, as well as rafts and layers of amphibolite and feldspar biotite schist. Unit is most commonly associated with positive gravity signatures. The magnetic signature of this unit is typically subdued, although body margins may be associated with curvilinear magnetic highs.

ACKNOWLEDGEMENTS

The U.S. Geological Survey provided funding as part of the 2009 State Geologic Survey Mapping Component (STATEMAP) of the National Geologic Mapping Program. Todd Petersen (Minnesota Department of Natural Resources) collected and processed data from ten seismic lines run in Sibley County for this map.

REFERENCES

Austin, G.S., 1970, Weathering of the Sioux Quartzite near New Ulm, Minnesota, as related to Cretaceous climates: Journal of Sedimentary Petrology, v. 40, p. 184-193.
Bickford, M.E., Wooden, J.L., and Bauer, R.L., 2006, SHRIMP study of zircons from early Archean rocks of the Minnesota River valley: Implications for the tectonic history of the Superior Province: Geological Society of America Bulletin, v. 118, p. 94-108.
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.
Boerboom, T.J., Setterholm, D.R., and Chandler, V.W., 1995, Bedrock geology, pl. 2 *of* Meyer, G.N., project manager, Geologic atlas of Stearns County, Minnesota: Minnesota Geological Survey County Atlas C-10, 7 pls., scales 1:100,000 and 1:200,000.
Chandler, V.W., Jirsa, M.A., and Boerboom, T.J., 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 Mossler, J.H., 2009, Supplemental bedrock geology, pl. 3 *of* Lusardi, B.A., project manager, Geologic atlas of McLeod County, Minnesota: Minnesota Geological Survey County Atlas C-20, 6 pls.
Grant, J.A., 1972, Minnesota River valley, southwestern Minnesota, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 177-198.
Hanson, G.N., 1968, K-Ar ages for hornblende from granites and gneisses and for basaltic intrusives in Minnesota: Minnesota Geological Survey Report of Investigations 8, 20 p.
Holm, D.K., Schneider, D., and Chandler, V.W., 2007, Proterozoic tectonic and crustal evolution of the upper Great Lakes region, North America: Precambrian Research, v. 157, p. 1-3.
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 continued 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. 17-26.
Humphrey, W.R., 1958, A study of the lithologic relations of the early Paleozoic and Cretaceous rocks in the Mankato, Minnesota area: Minneapolis, University of Minnesota, M.S. thesis, 110 p.
Jirsa, M.A., Boerboom, T.J., Chandler, V.W., Mossler, J.H., Runkel, A.C., and Setterholm, D.R., comps., 2011, Geologic map of Minnesota, bedrock geology: Minnesota Geological Survey State Map S-21, scale 1:500,000.
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.
Lund, E.H., 1950, Igneous and metamorphic rocks of the Minnesota River valley: Minneapolis, University of Minnesota, Ph.D. dissertation, 89 p., 21 pls.
Morey, G.B., 1977, Revised Keweenawan subsurface stratigraphy, southeastern Minnesota: Minnesota Geological Survey Report of Investigations 16, 67 p.
Mossler, J.H., 2008, Paleozoic stratigraphic nomenclature for Minnesota: Minnesota Geological Survey Report of Investigations 65, 76 p., 1 pl.
Parham, W.E., 1970, Clay mineralogy and geology of Minnesota's kaolin clays: Minnesota Geological Survey Special Publication SP-10, 142 p.
Pierce, R.L., 1961, Lower Upper Cretaceous plant microfossils from Minnesota: Minnesota Geological Survey Bulletin 42, 86 p.
Powell, L.H., 1935, A study of the Ozarkian faunas of southeastern Minnesota: St. Paul, Minn., St. Paul Institute of Science Museum Bulletin 1, 80 p, 17 pls.
Runkel, A.C., 1994a, Deposition of the uppermost Cambrian (Croixan) Jordan Sandstone, and the nature of the Cambrian-Ordovician boundary in the upper Mississippi valley: Geological Society of America Bulletin, v. 106, p. 492-506.
———1994b, Revised stratigraphic nomenclature for the Upper Cambrian (St. Croixan) Jordan Sandstone, southeastern Minnesota, *in* Southwick, D.L., ed., Short contributions to the geology of Minnesota: Minnesota Geological Survey Report of Investigations 43, p. 60-71.
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., Miller, J.F., McKay, R.M., Palmer, A.R., and Taylor, J.F., 2007, High-resolution sequence stratigraphy of lower Paleozoic sheet sandstones in central North America: The role of special conditions of cratonic interiors in development of stratal architecture: Geological Society of America Bulletin, v. 119, p. 860-881.
Runkel, A.C., Miller, J.F., McKay, R.M., Shaw, T.H., and Basset, D.J., 1999, Cambrian-Ordovician boundary strata in the central midcontinent of North America: Acta Universitatis Carolinae-Geologica, v. 43, p. 17-20.
Schmitz, M.D., Bowring, S.A., Southwick, D.L., Boerboom, T.J., and Wirth, K.R., 2006, High-precision U-Pb geochronology in the Minnesota River Valley subprovince and its bearing on the Neoarchean to Paleoproterozoic evolution of the southern Superior Province: Geological Society of America Bulletin, v. 118, p. 82-93.
Setterholm, D.R., 1990, Geologic maps of the Late Cretaceous rocks, southwestern Minnesota: Minnesota Geological Survey Miscellaneous Map M-69, scale 1:750,000, 2 pls.
Sloan, R.E., and Danes, Z.F., 1962, A geologic and gravity survey of the Belle Plaine area, Minnesota: Minnesota Academy of Science Proceedings, v. 30, p. 49-52.
Southwick, D.L., 2002, Geologic map of the pre-Cretaceous bedrock in southwestern Minnesota: Minnesota Geological Survey Miscellaneous Map M-121, scale 1:250,000.
Stauffer, C.R., and Thiel, G.A., 1941, The Paleozoic and related rocks of southeastern Minnesota: Minnesota Geological Survey Bulletin 20, 261 p.
Toth, T.A., 1996, Stratigraphy, mineralogy, and geochemistry of upper Cretaceous deposits from the Minnesota and Cottonwood River valleys, southwestern Minnesota: West Lafayette, Ind., Purdue University, Ph.D. dissertation, 199 p.
Upham, W., 1888, The geology of Sibley and Nicollet Counties, *in* Winchell, N.H., The geology of Minnesota: Geological and Natural History Survey of Minnesota, Final Report, v. 2, p. 148-179.