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 NICOLLET COUNTY BOARD OF COMMISSIONERS,
AND THE MINNESOTA ENVIRONMENT AND NATURAL RESOURCES TRUST FUND
AS RECOMMENDED BY THE LEGISLATIVE-CITIZEN COMMISSION ON MINNESOTA RESOURCES

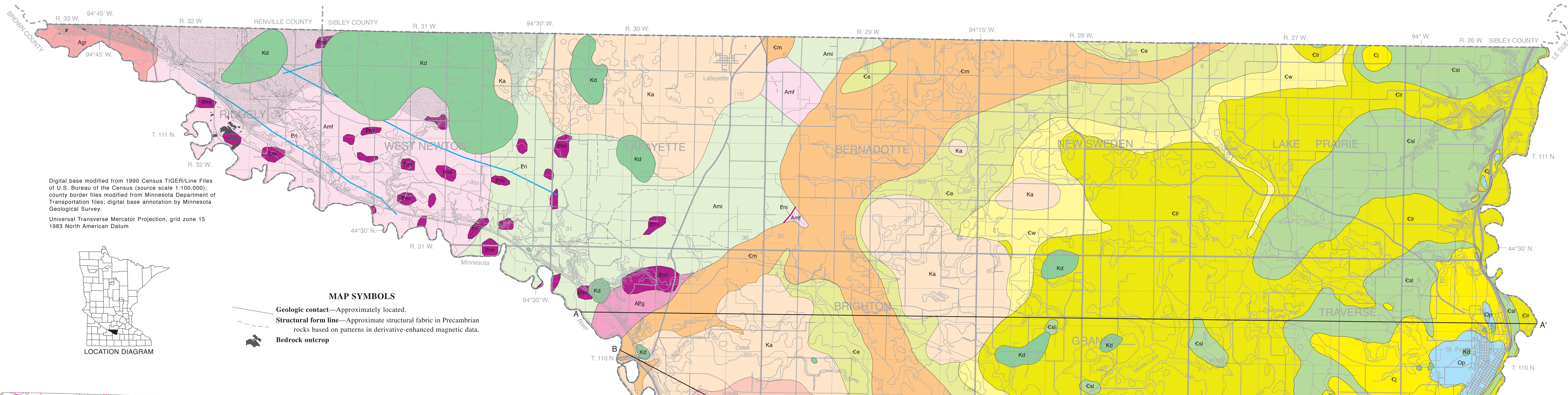
COUNTY ATLAS SERIES
ATLAS C-25, PART A
Nicollet County
Plate 2—Bedrock Geology

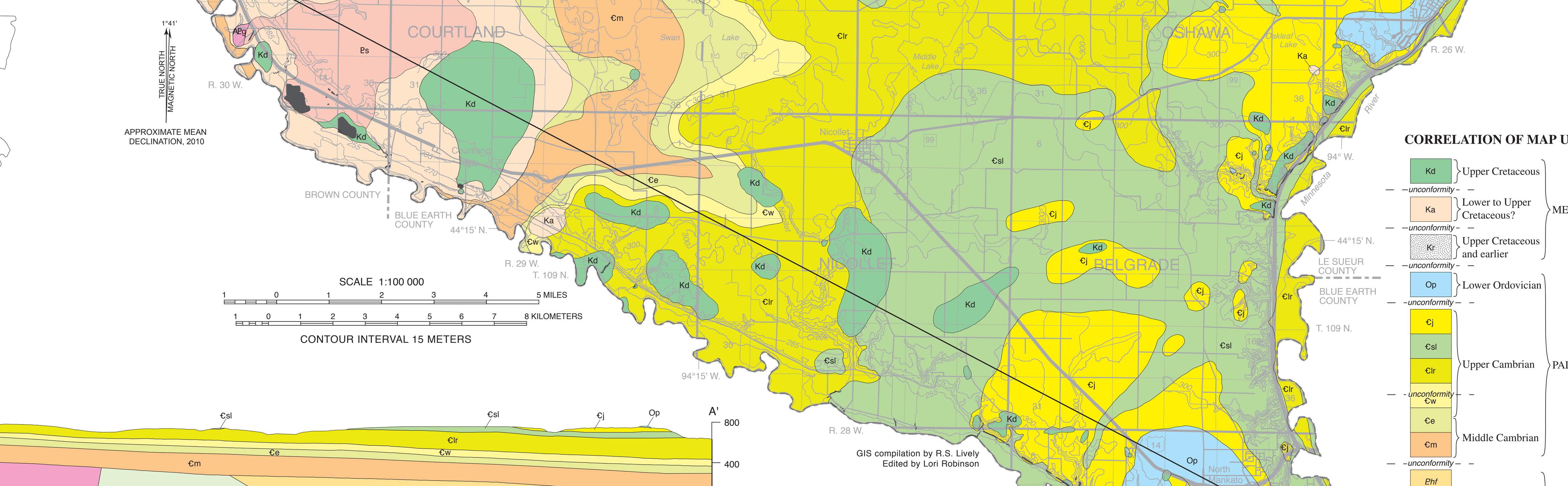
BEDROCK GEOLOGY

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

LOCATION DIAGRAM

MAP SYMBOLS

Geologic contact—Approximately located.

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

Bedrock outcrop

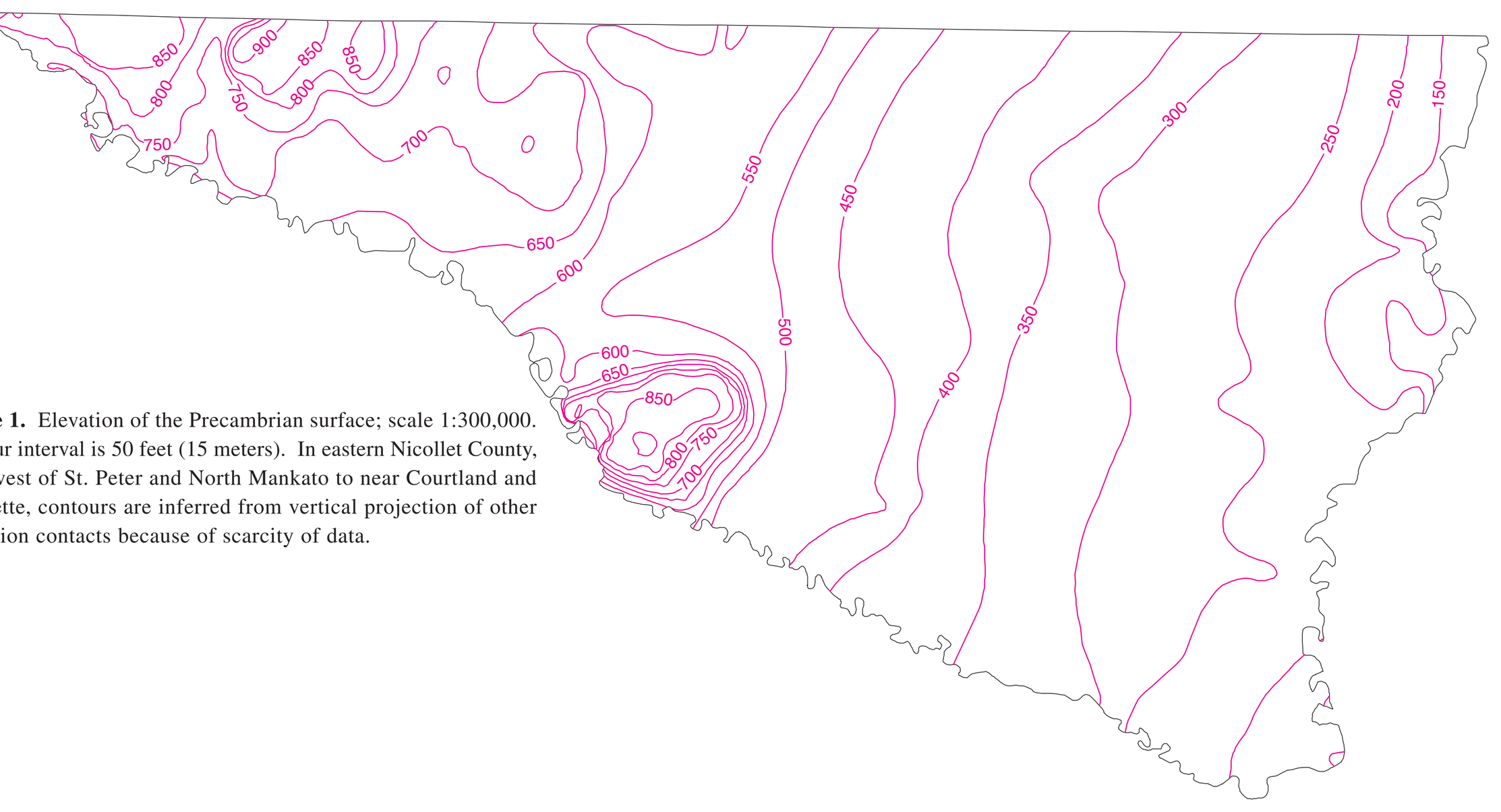
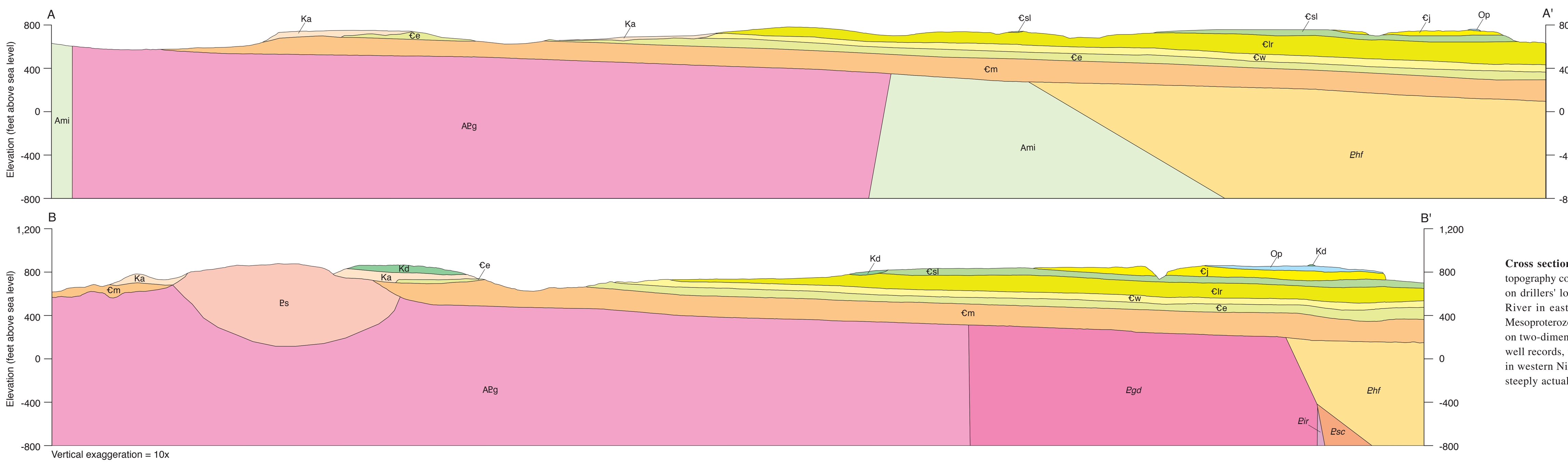
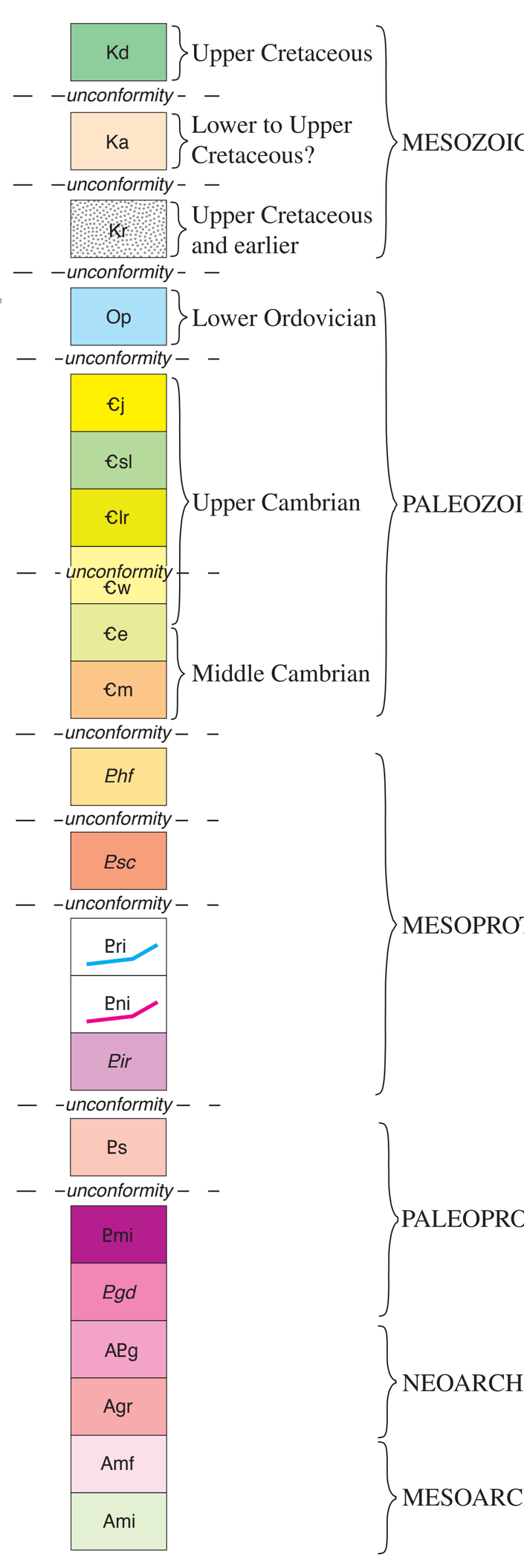


Figure 1. Elevation of the Precambrian surface; scale 1:300,000. Contour interval is 50 feet (15 meters). In eastern Nicollet County, from west of St. Peter and North Mankato to near Courtland and Lafayette, contours are inferred from vertical projection of other formation contacts because of scarcity of data.

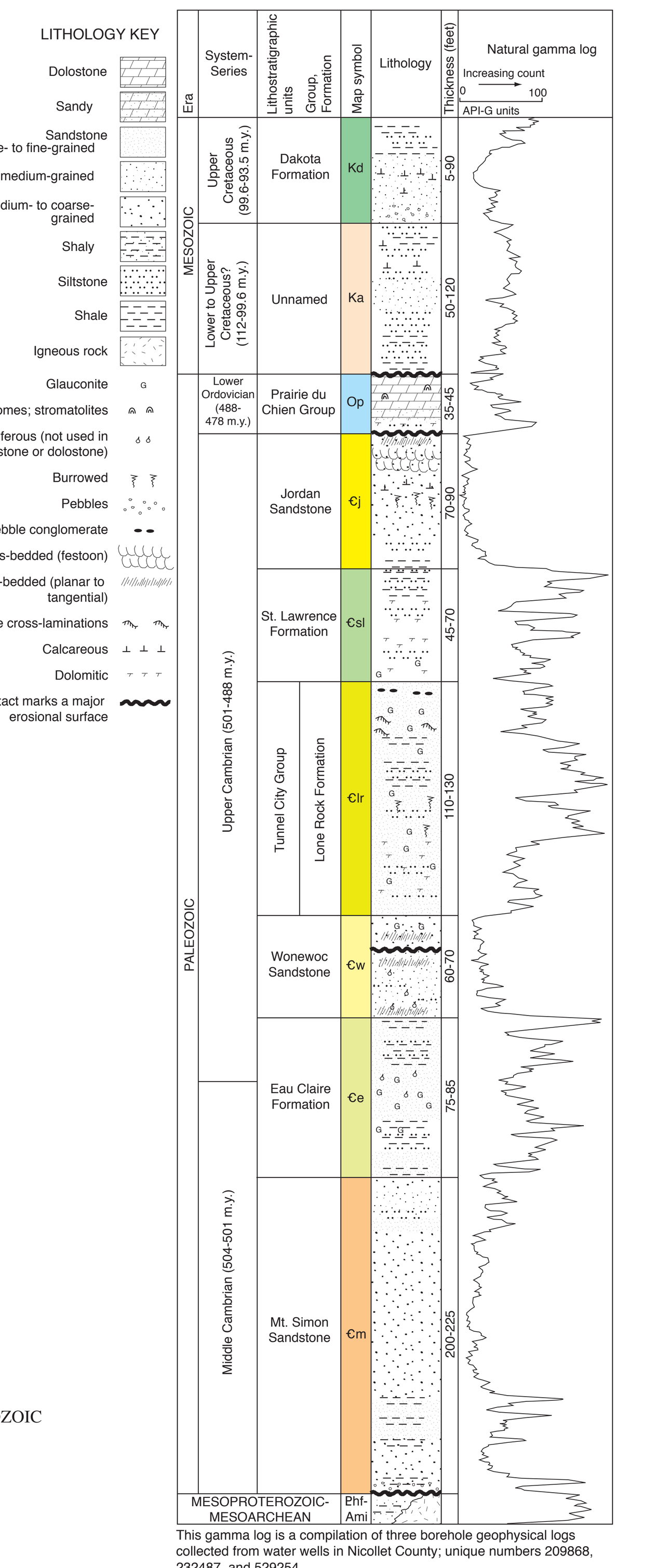


Cross sections—The contact between glacial deposits and bedrock is based on bedrock topography contours shown on the map. Contacts for Paleozoic and Mesozoic units are based on drillers' logs, water well cuttings, geophysical logs, and outcrops along the Minnesota River in eastern and south-central Nicollet County. Position and dip 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 in western Nicollet County. Due to vertical exaggeration (10x), features that appear to dip steeply actually dip at moderate angles, generally 35° to 50°.

CORRELATION OF MAP UNITS



STRATIGRAPHIC COLUMN



This gamma log is a compilation of three borehole geophysical logs collected from water wells in Nicollet County; unique numbers 209868, 232487, and 529254.

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 Nicollet 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 about 450 feet (137 meters). Bedrock exposures are limited to the eastern and southern parts of the county, along the Minnesota River and small tributaries. Therefore, bedrock geology must be generalized from available water well and engineering test boring records 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 mapping, geophysical surveys, and previous geologic mapping of Nicollet and adjacent counties, particularly mapping for the state bedrock geology map (Jirsa and others, 2010, 2011; see Plate 1, *Data-Base Map* for the distribution of data). Some seismic data were collected specifically for this STATEMAP mapping project by the Minnesota Department of Natural Resources (Todd Petersen) and the Minnesota Geological Survey (V.W. Chandler). The seismic data were collected in Sibley County to the north but helped to delineate buried bedrock valleys that extend into Nicollet County. Alan Knaeble, Minnesota Geological Survey, located and described some of the bedrock exposures used for mapping. Aeromagnetic and gravity data were particularly useful for mapping the 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 Nicollet County: Archean gneiss and granite, Paleoproterozoic mafic and intermediate rocks in plugs and dikes, Paleoproterozoic quartzite, and Paleozoic and Mesozoic sedimentary rocks.

Prominent bedrock valleys cross west-central Nicollet County and join a valley system to the north that crosses eastern Sibley County, northwestern LeSueur County, and western Scott County into southern Carver County and east. The Oneota Dolomite in eastern Nicollet County and the Sioux Quartzite in western Nicollet County form topographic highs on the bedrock surface because they were more resistant to erosion than the sandstone, siltstone, and shale underlying the buried valleys and depressions (cross section B–B'). Sioux Quartzite (unit Ps) ridges evidently have been topographically high areas since the early Paleozoic era because the Middle Cambrian Mt. Simon Sandstone (unit Cm) flanks it at a lower elevation (cross section B–B').

Buried stream channels 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 Nicollet County, the principal units of the bedrock surface are Paleozoic units that become progressively older from east to west. In western Nicollet County, the Paleozoic units have been stripped off and the principal rock formations are Precambrian gneiss, granite, and quartzite. Cretaceous sedimentary rocks were probably laid down across this bedrock surface as a continuous blanket, but because of subsequent erosion have been separated into scattered, discontinuous outliers.

There is little evidence for faults in the Paleozoic and Mesozoic rocks in the county. In part this may be due to the paucity of high quality subsurface data; however, the county is west of the western boundary of the Midcontinent Rift System and many of the faults observed in Paleozoic rocks in southern Minnesota appear to be the result of reactivation of Midcontinent Rift System faults. A Minnesota Department of Natural Resources observation well drilled in Courtland Township (T. 110 N., R. 29 W., sec. 31, NE) apparently crossed a fault within Sioux Quartzite, based on a pattern that indicated a repeated section of quartzite on the geophysical log and fractures observed in recordings by a color down-hole camera. However, it is difficult to extend the inferred fault or make any interpretation of its orientation based on an occurrence at a single site.

There are gentle folds in the Paleozoic strata. These are most evident in eastern Nicollet County where there are more water wells that penetrate Paleozoic strata, and particularly wells that cross the Lone Rock Formation–Wonewoc Sandstone contact, which is a useful horizon for mapping geologic structure.

DESCRIPTION OF MAP UNITS

MESOZOIC ROCKS

Mesozoic rocks occur as thin layers of sandstone, siltstone, dolostone, 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 and occurs as thin, discontinuous layers on top of the quartzite and Paleozoic rocks. It is interpreted to have formed during early Late Cretaceous time and earlier (Parham, 1970).

Kd **Dakota Formation (Upper Cretaceous)**—Claystone, shale, and sandstone. Light gray claystone and shale are as much as 25 feet (8 meters) thick near Courtland and up to 50 feet (15 meters) thick in Ridgely Township. The claystone and shale grades laterally into and overlies light gray to pale brown or yellow, fine- to coarse-grained quartz sandstone with thin beds of grayish-green to dark gray shale. The sandstone is up to 30 feet (9 meters) thick. The sandstone generally is friable but has variable cementation by iron oxide and calcite. It is cross-bedded or structureless and differs from Paleozoic quartz sandstone in that the grains are commonly subangular to angular. The sandstone contains clasts of kaolinite and thin layers of quartz and chert conglomerate. Claystone has numerous leaf impressions and iron-rich concretions. Both the sandstone and the shale contain dark gray to black lignitic material. The Dakota Formation has a thin basal conglomerate that is quartzose with abundant vein quartz and chert, and is dark reddish-brown to yellowish-gray in color. The matrix or cement of the conglomerate is commonly highly ferruginous, which gives the conglomerate its dark brown color. The chert pebbles contain fossils of Paleozoic, primarily Silurian and Devonian, age (Andrews, 1958) that may be sourced from the east in Wisconsin. Sand grains and pebbles in the conglomerate are characterized by smooth, highly polished surfaces. It varies from less than a foot to several feet in thickness.

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. 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 (229 and 268 meters). They reach a maximum thickness of about 90 feet (27 meters) in the Courtland area and west.

Compared to patchy strata classified as Cretaceous farther east by North Mankato and Judson (south of the Minnesota River in Blue Earth County), strata in western Nicollet County from the Courtland area and west can be assigned to the Cretaceous period with some confidence. The strata in western Nicollet Country are similar in lithic attributes and elevation to shale and sandstone from a clay pit near Courtland (Hu and others, 2008) and to strata in Brown County near New Ulm and at Fort Ridgely in extreme western Nicollet County (Pierce, 1961) that were dated by palynology. These studies indicate a Late Cretaceous age for the unit. The outcrops that were the subject of the palynological studies represent the easternmost extension of a large, nearly continuous subcrop area of strata correlated with the Late Cretaceous Dakota Formation (Setterholm, 1990). The 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). The basal conglomerate is interpreted to be equivalent to the Ostrander Conglomerate of southeastern Minnesota.

Cretaceous sedimentary strata in Nicollet County have some economic uses. A few wells draw water entirely from Cretaceous sandstone. About 2 miles (3 kilometers) west of Courtland, shale beds are mined for use as raw material for bricks and modeling clay (Zanko and others, 1998).

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 Nicollet County west of Courtland, where it reaches 120 feet (37 meters) or more; however, more commonly it is 50 to 60 feet (15 to 18 meters) or less in thickness. A thin bed of terra rosa, reddish-brown residual soil commonly found mantling carbonate bedrock in karst areas, is present on top of Oneota Dolomite of the Prairie du Chien Group in a municipal well at St. Peter. It may be equivalent to the basal part of the unit. Distinguishing the undifferentiated unit from weathered, fine-grained Paleozoic rocks and from the saprolith on top of the Precambrian granitic rocks can be difficult, particularly on drillers' logs. The unit unconformably overlies the Precambrian crystalline rocks and Paleozoic formations ranging in age from Middle to Late Cambrian and possibly Ordovician. Exposures of the unit along the Minnesota River and small tributary streams from Courtland to New Ulm were described by Austin (1970), who considered them to be Late Cretaceous in age and postdate the saprolith (unit Kr). 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 are clearly Cretaceous and 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 derived primarily from the weathering of Precambrian granitic and gneissic rocks. Where it overlies granite or gneiss, it grades down from the 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 (Parham, 1970). An organic-rich clay in a reworked interval to the northwest in Renville County contains pollen of Late Cretaceous age (John Hall, 1969, unpub. data in Parham, 1970, p. 9). The saprolith is thickest in the western part of Nicollet County where it overlies granitic bedrock and thins eastward, where it overlies Paleozoic sedimentary rocks and occupies cavities in karsted carbonate rocks. The saprolith is about 80 feet (24 meters) thick in a test hole drilled in Ridgely Township, but thickness variations are poorly constrained elsewhere because the unit is not an aquifer and most drillers stop near the top of the unit. The saprolith is mined for clay for brick and artwork to the west in Brown County (T. 111 N., R. 32 W., sec. 17, NE) and to the northwest in Renville County (T. 112 N., R. 32 W., sec. 31, NE; Zanko and others, 2005).

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 about 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 (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. This dolostone is principally equivalent to the Hager City Member of the Oneota Dolomite of the Prairie du Chien Group in southeastern Minnesota. However, thin remnants of the overlying Shakopee Formation of the Prairie du Chien Group may be present at some locations.

The Hager City Member is not quarried at present, as it has been in the past at North Mankato and St. Peter, but it is mined extensively for building-stone and aggregate products directly south across the Minnesota River in Blue Earth County. Large (meter-scale) solution enhanced vertical joints and bedding plane fractures are particularly common in the Hager City Member. 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 of the Oneota Dolomite and may be siltstone that was squeezed up into the 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.

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 and conformably underlies the Blue Earth Member 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 Prairie du Chien Group is up to 40 feet (12 meters) thick in Nicollet County, thinner than the maximum thicknesses observed elsewhere in southern Minnesota where it has not been subjected to pre-Quaternary period erosion as it has been everywhere in Nicollet County. The formation is present in the eastern part of the county mostly near North Mankato and St. Peter, where it is highly dissected and occurs as erosional remnants on top of the underlying Jordan Sandstone (Cj). It also crops out at North Mankato in the bluffs along the Minnesota River.

Cj **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 (Csl), although there are lithologically similar intervals intercalated with the medium- to coarse-grained facies at higher stratigraphic intervals. Exposures along the Minnesota River west of Mankato 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 Nicollet County. It is present in the subsurface in eastern Nicollet County at North Mankato and St. Peter and westward from those towns. The Jordan Sandstone crops out extensively in the bluffs along the Minnesota River immediately to the west of North Mankato, along Seven Mile Creek, and in nearby banks of the Minnesota River south of St. Peter.

The Jordan Sandstone is mined to the east in LeSueur County for silica sand that is used in various products including frac sand in the oil and gas industry.

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

The St. Lawrence Formation is 45 to 70 feet (14 to 21 meters) thick where it is undissected by erosion. It subcrops extensively in the eastern part of the county and outcrops along the Minnesota River valley just north and to the east of Judson in Blue Earth 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 (Clr) is conformable. It is characterized by 3 to 7 feet (1 to 2 meters) of interbedded glauconitic, intraclastic dolostone and sandstone.

The dolostone beds in the St. Lawrence Formation exposed near Judson in Blue Earth County to the south commonly have solution features typical of karstic carbonate rock.

Clr **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. Dolostone beds are thin to medium-thick, pink-orange-gray to dark red, commonly intraclastic, and most abundant in the lower one-third of the formation where the basal 10 to 12 feet (3 to 4 meters) is mostly sandy dolostone. Phosphatic brachiopods are common in this interval.

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. There are small exposures along the southern shore of the Minnesota River by Judson in Blue Earth County and to the west.

Cw **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 and below 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.

Ce **Eau Claire Formation (Middle to Upper Cambrian)**—Sandstone with minor shale and siltstone. The sandstone is light gray to yellowish-gray and light brown, very fine- to fine-grained, and feldspathic. 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 numerous phosphatic brachiopod valves as well as hyolithids and trilobite fragments. It is glauconitic, especially in its lower part. The contact with the underlying Mt. Simon Sandstone 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).

Cm **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 light gray, feldspathic, very fine-grained sandstone that generally are more abundant in the upper part of the sandstone. The upper part has inarticulate brachiopod valves. The basal part has more very coarse-grained to granular sandstone and there 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). The basal contact of the Mt. Simon Sandstone with Precambrian formations is an unconformity. The Mt. Simon Sandstone overlies Mesoproterozoic Hinckley Sandstone, Paleoproterozoic Sioux Quartzite, and Neoarchean and Mesoarchean rocks, principally the Morton Gneiss and Fort Ridgely Granite (Southwick, 2002; cross sections A–A', B–B').

MESOPROTEROZOIC ROCKS

Paleozoic bedrock in eastern Nicollet 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). Although sedimentary rocks of the Midcontinent Rift extend beneath eastern Nicollet County, most of the rift-related igneous rocks are found from 12 to 47 miles (20 to 75 kilometers) to the east.

Phf **Hinckley Sandstone and Fond du Lac Formation** (shown only on cross sections)—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 and is discontinuous. The Hinckley Sandstone and Fond du Lac Formation are not known to subcrop beneath Quaternary sediments in Nicollet County and therefore are not shown on the bedrock geologic map.

Psc **Solor Church Formation** (shown only on cross section B–B')—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, containing 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 the faulting of Mesoproterozoic rocks. It is underlain by volcanic rocks, primarily basalt. The Solor Church Formation is not known to subcrop beneath Quaternary sediments in Nicollet County and therefore is not shown on the bedrock geologic map.

Pri **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 (Chandler and others, 2008) or 2,067 Ma dikes in southwestern Minnesota (Schmitz and others, 2006).

Pni **Northeast-trending dikes**—Positive magnetic anomaly signatures in derivative-enhanced magnetic data imply normal magnetic polarity. Magnetic data imply that the dikes are more abundant to the east, toward the Midcontinent Rift, and they may therefore be related to this feature.

Pir **Reversely polarized intrusive rock** (shown only on cross section B–B')—Unit is inferred largely from geophysical data. Rock is characterized by a pronounced, linear low in the magnetic data and a generally positive gravity signature. Based on proximity, the intrusion is inferred to be related to the Midcontinent Rift.

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 Nicollet 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 that are inferred in western Nicollet County (see unit Pni) could plausibly reflect this event as well. Some of the other intrusive rocks that are inferred beneath Nicollet County (units Pgd, Pmi, and possibly APg) 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). Following the Yavapai Orogeny, the Sioux Quartzite is interpreted to have been deposited between 1,750 and 1,630 Ma (Holm and others, 1998), predominantly in a distal braided river-alluvial plain environment, although the upper third of the formation has some features that are consistent with a shallow marine, tidally influenced environment (Ojakangas and Weber, 1984).

Ps **Sioux Quartzite**—Pink to red to maroon and gray, very fine- to coarse-grained quartzite and dark red to green-gray, hard, micaceous, siliceous shale. The quartzite is cross-stratified and contains intercalated beds of mudstone and argillaceous orthoquartzite in its lower part (Ojakangas and Weber, 1984). The upper part contains thin to thick layers of conglomeratic orthoquartzite. It is cemented with authigenic quartz and chert. There is a basal conglomerate west of the main outcrop area that contains clasts of vein quartz, chert, iron-formation, and quartzite. Ojakangas and Weber (1984) reported that 705 feet (215 meters) of Sioux Quartzite is exposed intermittently west of Courtland, at and near the New Ulm Quartzite quarry. In addition, 62 feet (19 meters) of basal conglomerate is exposed 1.25 to 1.5 miles (2 kilometers) west of the main exposures just north of New Ulm in Nicollet County (Ojakangas and Weber, 1984). The estimated total thickness from measured sections is 847 feet (258 meters). The thickness observed in a test well drilled at the New Ulm Quarry was 676 feet (206 meters); however, the well did not reach the base of the Sioux Quartzite.

The Sioux Quartzite is quarried near Courtland for rock aggregate.

Pmi **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 Pgp 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 northwest in Redwood County include the Franklin diabase dike, which has yielded a Pb-Pb age of 2,067 ± 1 Ma (Schmitz and others, 2006), and the gabbro-granophyre of the Cedar Mountain Complex, which has yielded a K-Ar hornblende age of 1,750 Ma (Hanson, 1968).

Pgd **Proterozoic intermediate granitoid rocks** (shown only on cross section B–B')—Inferred wholly from geophysical data. Rocks characterized by a subdued magnetic signature and a positive gravity signature. Inferred to be of Yavapai Orogeny affinity.

ARCHEAN ROCKS

Western Nicollet 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).

Neoarchean rocks

APg **Granite at New Ulm**—Porphyritic foliated granite of either Archean or early Paleoproterozoic age. Unit is mapped largely on the basis of a pronounced gravity low that extends 12 to 31 miles (20 to 50 kilometers) to the east and southeast from the outcrop area near New Ulm. The magnetic signature is generally subdued. The negative gravity signature resembles that of the Sacred Heart Granite to the west in northern Redwood County, which has yielded U-Pb ages of 2,603 ± 1 Ma and 2,592 ± 1 Ma (Schmitz and others, 2006). The Fort Ridgely Granite, which is generally thought to be contemporaneous with the Sacred Heart Granite (Southwick, 2002), lies only about 19 miles (30 kilometers) northwest of New Ulm. However, the area to the southeast of New Ulm is interpreted to include a significant fraction of Paleoproterozoic intrusions (Jirsa and others, 2010, 2011), and a Paleoproterozoic age for the granite at New Ulm cannot be ruled out at this time.

Agr **Fort Ridgely Granite**—Porphyritic, well foliated granite, commonly with locally abundant schlieren, of more mafic material (Grant, 1972). The gravity and magnetic signatures associated with this body are somewhat obscure. Thus the granite may not represent a discrete pluton, but instead may be a well-incorporated phase within the Morton Gneiss, as was postulated by Lund (1956). No precise age-dates currently exist for the Fort Ridgely Granite, but it is generally thought to be contemporaneous with the 2,595 to 2,603 Ma Sacred Heart Granite to the west in northern Redwood County (Southwick, 2002). Granitic phases of the Morton Gneiss that might also correlate with the Fort Ridgely 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).

Mesoarchean rocks

Morton Gneiss—As described by Southwick (2002), this rock is generally quartzofeldspathic in composition, and commonly includes tonalitic and granitic and granodioritic phases, as well as rafts and layers of amphibolite and biotitic schist (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 at the western edge of Nicollet County (Lund, 1950). To the west of Nicollet 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 and Fort Ridgely Granites 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 Nicollet 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 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. The magnetic signature of this unit is typically subdued, although body margins may be associated with curvilinear magnetic highs. Unit is most commonly associated with positive gravity signatures.

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. Alan Knaeble located and described some of the bedrock exposures used in mapping the bedrock geology.

REFERENCES

Andrews, G.W., 1958, Windrow Formation of upper Mississippi valley region, a sedimentary and stratigraphic study: Journal of Geology, v. 66, p. 597-624.

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.

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.

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., Schneider, D., and Coath, C.D., 1998, Age and deformation of Early Proterozoic quartzites in the southern Lake Superior region: Implications for extent of foreland deformation during final assembly of Laurentia: Geology, v. 26, p. 907-910.

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., 2010, Preliminary bedrock geologic map of Minnesota: Minnesota Geological Survey Open-File Report 10-02, scale 1:1,000,000.

———comps., 2011, Geologic map of Minnesota, bedrock geology: Minnesota Geological Survey State Map S-21, scale 1:500,000.

Lund, E.H., 1950, Igneous and metamorphic rocks of the Minnesota River valley: Minneapolis, University of Minnesota, Ph.D. dissertation, 89 p., 21 pls.

———1956, Igneous and metamorphic rocks of the Minnesota River valley: Geological Society of America Bulletin, v. 67, p. 1475-1490.

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.

Ojakangas, R.W., and Weber, R.E., 1984, Petrography and paleocurrents of the Proterozoic Sioux Quartzite, Minnesota and South Dakota, *in* Southwick, D.L., ed., Shorter contributions to the geology of the Sioux Quartzite (Early Proterozoic), southwestern Minnesota: Minnesota Geological Survey Report of Investigations 32, p. 1-15.

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.

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.

Zanko, L.M., Heine, J.J., and Setterholm, D.R., 2005, Geology of the Pre-Cretaceous weathering profile and Cretaceous strata of the Minnesota and Cottonwood River valleys, field trip 8, *in* Robinson, L., ed., Field trip guidebook for selected geology in Minnesota and Wisconsin: Minnesota Geological Survey Guidebook 21, p. 144-153.

Zanko, L.M., Oreskovich, J.A., Heine, J.J., Grant, J.A., Setterholm, D.R., and Hauck, S.A., 1998, Mapping industrial clay potential in the Minnesota River valley: Natural Resources Research Institute, Report of Investigations NRRI/RI-98/03, 53 p.