UNIVERSITY OF MINNESOTA
MINNESOTA GEOLOGICAL SURVEY
Harvey Thorleifson, Director

Prepared and Published with the Support of
THE BENTON COUNTY BOARD OF COMMISSIONERS AND
THE MINNESOTA ENVIRONMENT AND NATURAL RESOURCES TRUST FUND
AS RECOMMENDED BY THE LEGISLATIVE-CITIZEN COMMISSION ON MINNESOTA RESOURCES

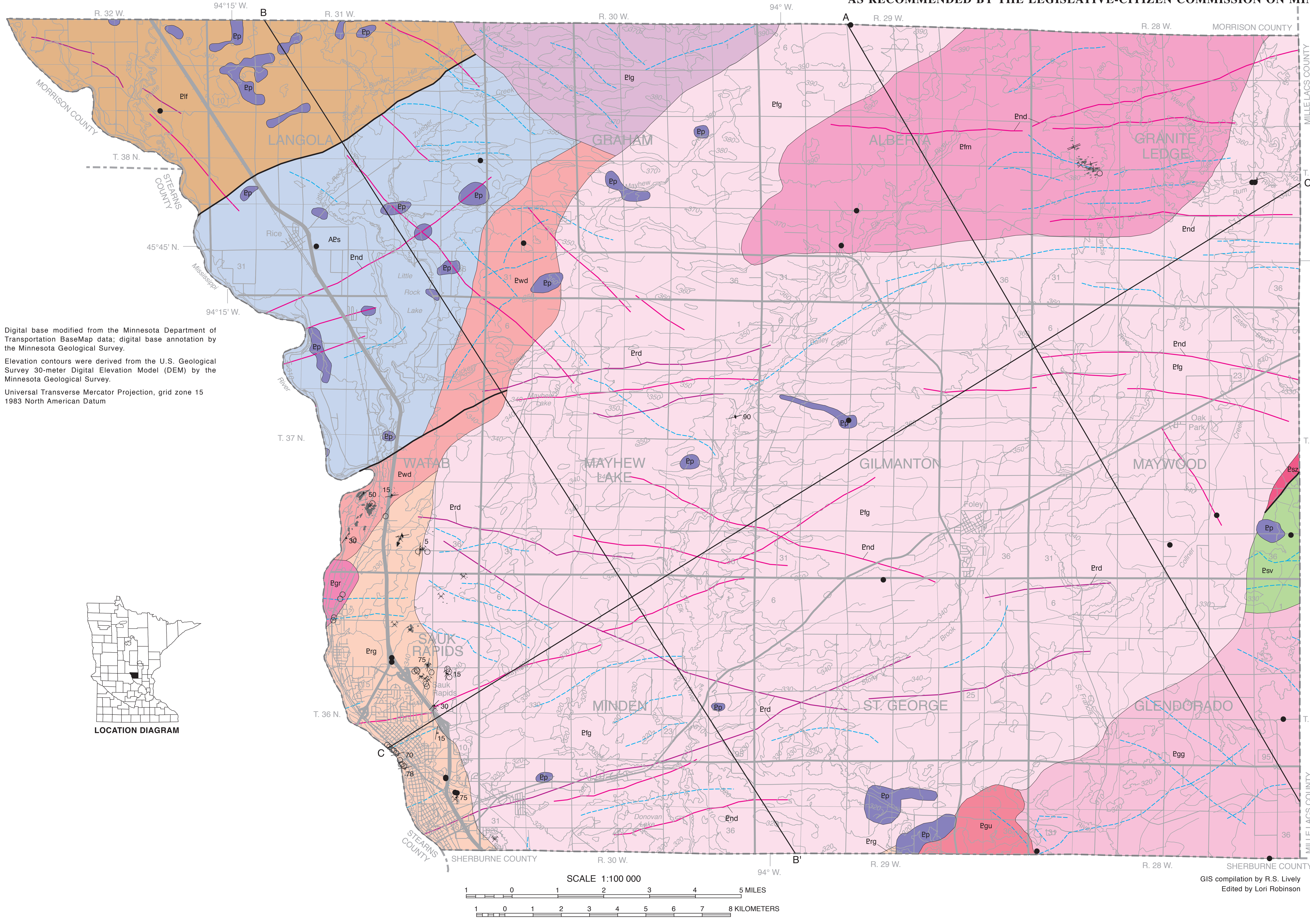


# BEDROCK GEOLOGY

By

Mark A. Jirsa and V.W. Chandler

2010



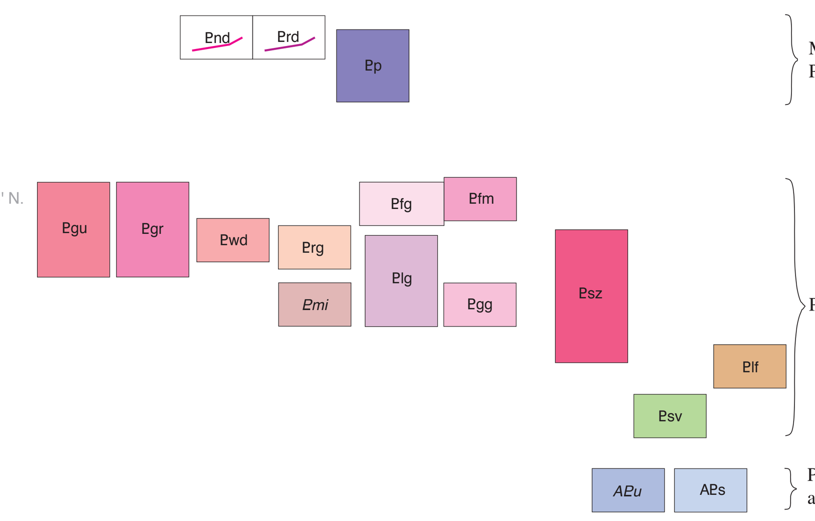

Digital base modified from the Minnesota Department of Transportation BaseMap data; digital base annotation by the Minnesota Geological Survey.

Elevation contours were derived from the U.S. Geological Survey 30-meter Digital Elevation Model (DEM) by the Minnesota Geological Survey.

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

LOCATION DIAGRAM

## CORRELATION OF MAP UNITS




## MAP SYMBOLS

**Inferred contact**—Located mostly from aeromagnetic maps.

**Inferred fault**—Located mostly from aeromagnetic maps; offset unknown.

**Narrow aeromagnetic anomaly**—Inferred to represent the trajectory of foliation and dike trend in the bedrock. Note that some of the linear anomalies visible on Figure 4, particularly those trending east, are not mapped as bedrock anomalies because they appear to be the product of near-surface glacial landforms.

**Strike and dip of magmatic foliation**—Inclined, vertical.

**Strike and dip of metamorphic foliation**—Includes cleavage and schistosity; inclined, vertical.

**Trend and plunge of mineral lineation.**

**Strike and dip of a small diabasic dike** (units Ꝑnd, Ꝑrd)—Inclined, vertical.

**Strike and dip of a small granitic dike**—Includes quartz feldspar porphyry and dikes of aplite and microgranite; inclined, vertical.

**Drill hole for which some bedrock sample material exists**—Includes holes drilled by the Minnesota Geological Survey, Minnesota Department of Transportation, and exploration companies.

**Bedrock outcrop, observed**—Includes areas of closely spaced small outcrops.

**Bedrock outcrop, inferred**—General locations of outcrop reported in Ellingson (2002); not visited by the authors.

**Quarry**—Horizontally crossed symbol indicates an abandoned quarry; uncrossed symbol represents a proposed quarry in Granite Ledge Township, northeastern Benton County.

A—A' **Location of line of geophysical section (Fig. 1).**

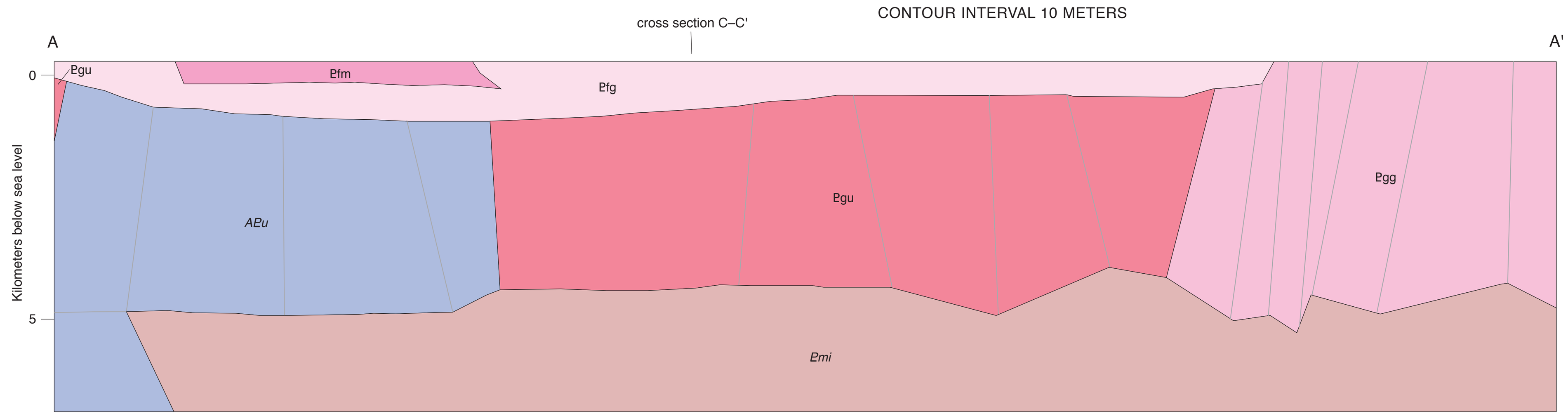
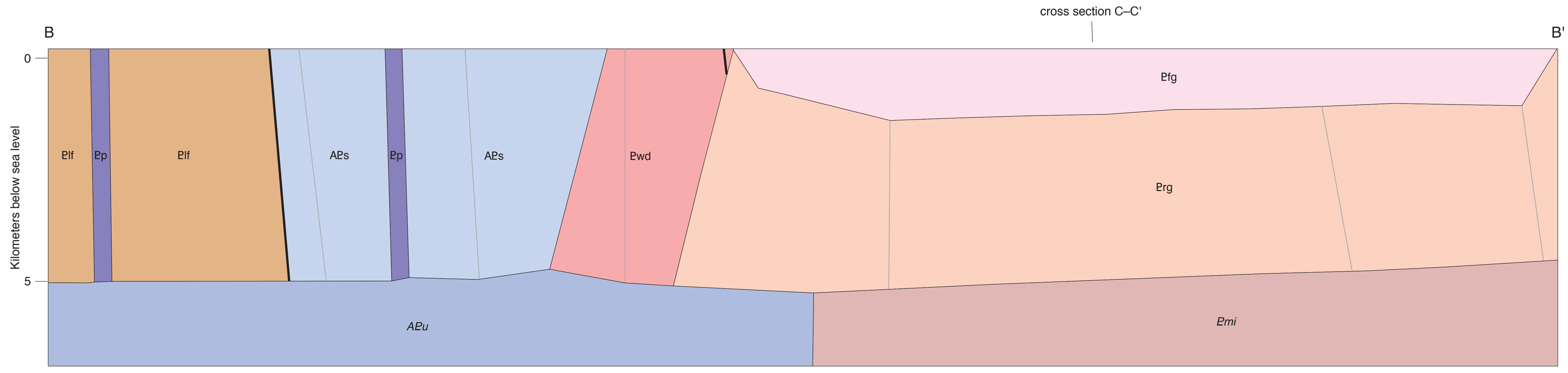
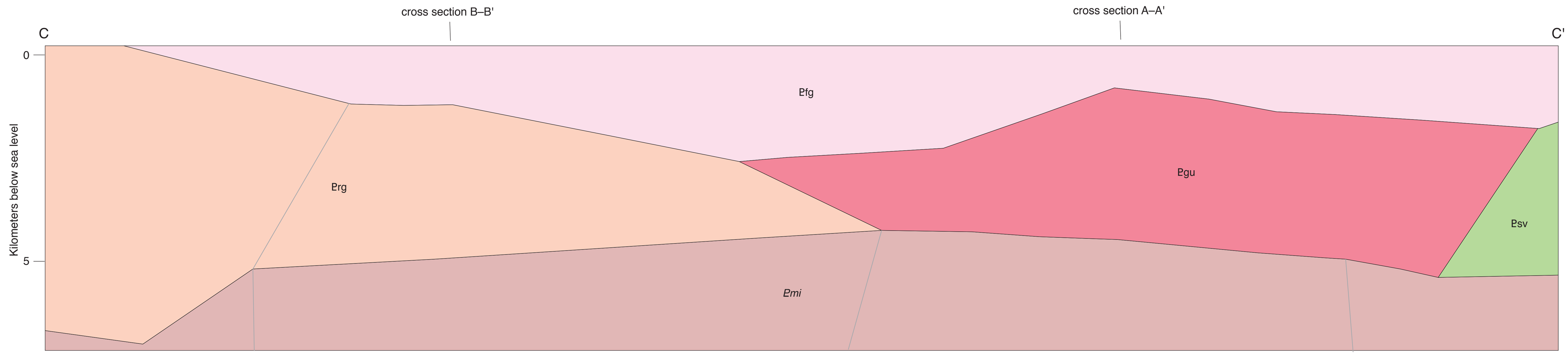



**Figure 1.** Geologic cross-sections showing subsurface structure, based on the modeling of gravity and magnetic data. Lines designating faults and contacts are the same as used for the geologic map. The inferred structural grain of subsurface geology is indicated by gray lines, which represent boundaries between contrasting bodies from the modeling. Due to their minimal thicknesses, neither dikes nor glacial deposits are shown on the sections. Bodies shown below 3 miles (5 kilometers) actually extend to 9 miles (15 kilometers) depth in original models. No vertical exaggeration was used in any section.



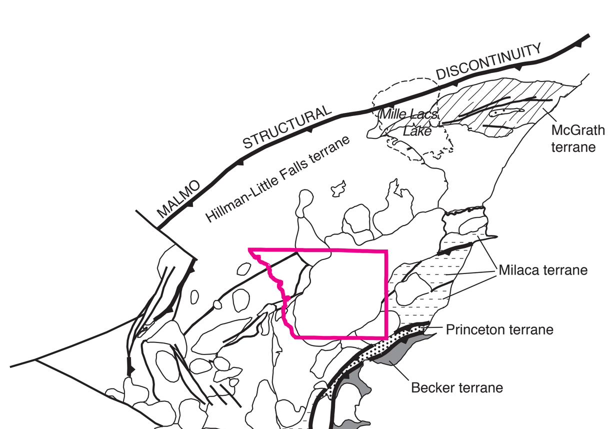




**Figure 3.** Schematic map showing major geologic terranes in east-central Minnesota that are separated by faults. One such fault structure, the Malmo structural discontinuity, separates continental-type rocks to the north from diverse terranes locally containing arc-type volcanic rocks to the south.

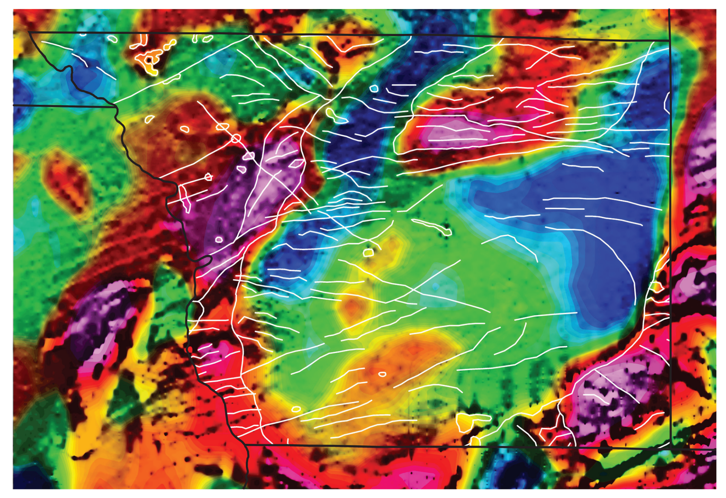



**Figure 4.** Superimposed geophysical images of first vertical derivative magnetic anomaly data (gray scale) and second vertical derivative gravity data (color) for the Benton County area. The range of first vertical derivative magnetic values is approximately -200 (black) to 200 (white) nanoTesla/km, and the range of second vertical derivative gravity values is approximately -0.25 (blue) to 0.25 (magenta) milligals/km$^2$. County boundaries are shown as black lines, and geologic contacts, dikes, and faults are shown by white lines. 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 are used in conjunction with existing information from outcrops and drill-holes to produce the bedrock geologic map.

## INTRODUCTION

This map depicts the distribution of bedrock units that are largely buried beneath glacial and recent sediments in Benton County. It is modified from prior mapping by Jirsa and others (2003) on the basis of newly reprocessed geophysical data and geophysical models (Fig. 1; Chandler, 2007; Chandler and others, 2008), new drilling of rotary-sonic core holes by the Minnesota Geological Survey (see Plate 3, *Surficial Geology*), and recently compiled water well records. Because of the scarcity of bedrock outcrops, most of the prior mapping was based on geophysical interpretation augmented by information from water-well records, exploration and engineering test holes, and 40 core holes drilled specifically to test geophysical interpretations. Those data are summarized in Jirsa and Chandler (1997).

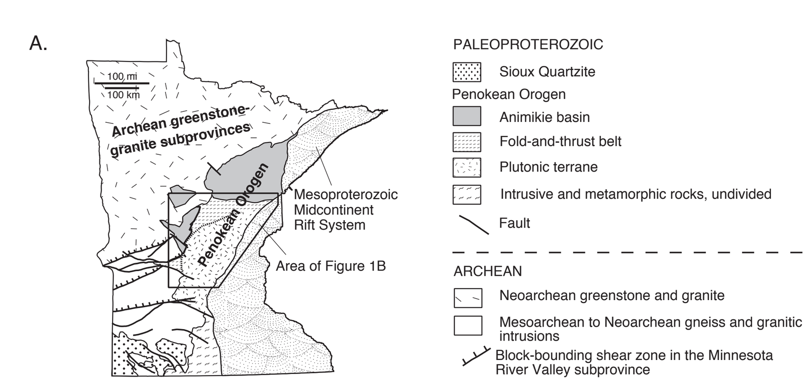
The bedrock of Benton County consists of rock units that may be as young as Mesoproterozoic (~1,100 million years old [Ma]) and as old as Archean age (~2,600 Ma). The majority, however, are Paleoproterozoic age (~1,800 Ma). The interpretation depicted here reflects the concept established by Southwick and Morey (1991) of thrust imbrication of variably related terranes during the Penokean Orogeny, a period of crustal-scale compressional deformation that culminated at about 1,850 Ma (Fig. 2A). This zone of deformation is nearly continent-wide, based on evidence that appears discontinuously in the bedrock from Michigan to Wyoming. The orogen—the "rock-product" of orogeny—is manifest in the generally arcuate pattern of geologic units and faults shown on Figure 2B. The Archean units and portions of the Paleoproterozoic units are subdivided into terranes that are named on Figure 3. The terranes are inferred to be separated by thrust faults, along which disparate types of rock were tectonically stacked and metamorphosed during the Penokean Orogeny. Within that framework, the bulk of the geologic map of Benton County portrays a large and complex suite of younger intrusions that were emplaced subsequent to Penokean orogenesis, and are known collectively as the East-Central Minnesota Batholith (Van Schmus and others, 2000). One of the largest intrusions of the batholith is the Foley Granite, which comprises much of the bedrock in the county. Exposures of the Foley Granite are prominent in Granite Ledge Township in the northeastern part of the county (T. 38 N., R. 28 W.). A crushed rock aggregate quarry is proposed in that township. The western part of the county contains scattered outcrops and historic, abandoned quarries in the Foley Granite and adjacent units.

The relative emplacement ages of the various intrusions within the East-Central Minnesota Batholith are difficult to establish in this area of only scattered bedrock exposure. Nevertheless, outcrops along the western edge of the Foley Granite (unit Ꝑfg), near the contact with the Reformatory Granodiorite (unit Ꝑrg), give some clues. The granodiorite contains abundant dikes and irregular intrusions of red granite similar to the Foley Granite; the Foley Granite locally contains inclusions of gray granodiorite like the Reformatory Granodiorite. Collectively, these observations indicate that the Foley Granite is the younger of the two intrusions. Subsequent to the drilling of 40 test holes by the Minnesota Geological Survey (Jirsa and Chandler, 1997), and mapping in adjacent areas (for example, Boerboom and others, 1995), a concerted effort was made to unravel the temporal context for the complex terrane in east-central Minnesota using geochronologic analyses. The dating techniques were applied to samples taken from drill core and outcrop. They included both $^{40}Ar/^{39}Ar$ analyses of what is inferred to be magmatic biotite and hornblende, and U-Pb analyses of zircons. Because zircons are resistant to alteration, the U-Pb dates closely represent crystallization ages of the various intrusions—plus or minus a few million years. By contrast, the $^{40}Ar/^{39}Ar$ dates are somewhat less certain because chemical changes to biotite and hornblende are possible during thermal or chemical alteration after crystallization. The data are summarized and discussed in Holm and others (2005), and to a lesser extent in Jirsa and others (2006). Those dates pertinent to the geology of Benton County are given here in the Description of Map Units. The new age dates indicate that emplacement and crystallization of intrusions comprising the East-Central Minnesota Batholith span as much as 19 million years, from about 1,773 to 1,792 Ma (considering limits of error).

Much of the buried bedrock in the county (as elsewhere in Minnesota) is covered with a discontinuous and variably thick horizon of clayey material called saprolite. Saprolite formed by intense chemical weathering of bedrock over a period of millions of years. Many of the holes drilled for prior regional mapping and the rotary-sonic core holes drilled for this project intersected saprolite, which is locally as thick as 250 feet (76 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. Individual minerals within a rock alter to differently colored clay that indicates the mineral's original composition—plagioclase weathers to white clay, iron- and magnesium-rich minerals weather to green clays, and iron oxides become hydrated to form goethite or limonite. Typically mica and quartz are little affected by the weathering process. Although the rocks are severely altered, remnants of foliation and layering are locally preserved. The common "whale-back" shape of many outcrops in Benton County can be attributed in part to the removal of saprolite from the solid rock surface by glaciation and other types of erosion (Patterson and Boerboom, 1999).

Because of poor exposure, mapping of the Precambrian bedrock beneath Benton County relies significantly on indirect examination using gravity data, which is sensitive to density variations in the bedrock, and magnetic data, which is 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), and gravity and magnetic data are consequently effective tools for bedrock mapping in this region. The gravity data are from a statewide compilation (Chandler and Schaap, 1991), and in Benton County are based on ground stations taken roughly 1 mile (1.6 kilometers) apart. The reduced data (Bouguer anomaly) for the Benton 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. The aeromagnetic (airborne magnetic) data were acquired as part of a statewide survey program (Chandler, 1991), and in Benton County the data were acquired using north-south lines, which were flown 1,312 feet (400 meters) apart and 492 feet (150 meters) above the ground in the northern part of the county, and 1,640 feet (500 meters) apart and 656 feet (200 meters) above the ground in the southern part of the county. The aeromagnetic grid used here was derived from a recently composited, 328-foot (100-meter) grid of the state (Chandler and others, 2008), where the data were analytically continued to a common level of 492 feet (150 meters) above the ground. To enhance the magnetic data for geologic mapping, the first and second vertical derivatives of the anomaly data were calculated. The effectiveness of mapping bedrock features with derivative-enhanced gravity and magnetic data is demonstrated in Figure 4, 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). Digital files of the original and derivative-enhanced gravity and magnetic data are available on the compact disc that accompanies this atlas.

In order to investigate geologic structure at depth and to produce geologic cross-sections (Fig. 1), gravity and magnetic modeling was conducted along three sections. Modeling was two-dimensional (strike-infinite sources), although end corrections were allowed for finite-strike sources. To assure reliable modeling up to the margins of Benton County, the model profiles extended considerably beyond the ends of the cross-sections shown on the bedrock map. Numerous iterations were necessary to fit the observed anomalies along each profile, and to attain consistency between the three models at their intersections. Geologic interpretation of the resulting models was constrained by the geologic map of the bedrock surface and by existing rock property data (Chandler and others, 2008). The results indicate that most of the gravity and magnetic signatures can be accounted for by steeply-dipping units, although some of the contacts associated with the Foley Granite are low-dipping, implying a tabular form for much of this unit. Most anomaly signatures could be accounted for by geologically reasonable sources lying within the upper 3 miles (5 kilometers) of the crust, but some magnetic units were extended down to 9 miles (15 kilometers) to better accommodate some of the longer-wavelength anomaly signatures in the area. In earlier model studies in east-central Minnesota, Chandler and others (2008) speculated that these deeper magnetic bodies may represent granodioritic rocks, whereas the intervening non-magnetic areas might represent metamorphic rocks. Digital files of the models are available on the accompanying compact disc for this atlas.



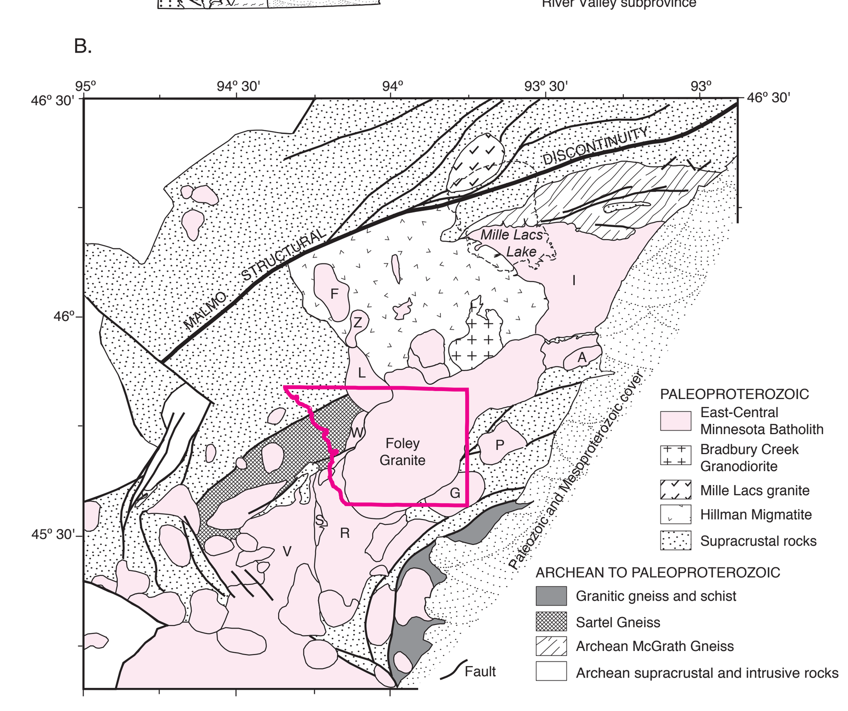




**Figure 2.** Generalized bedrock geologic maps of Minnesota.

**A.** Bedrock geology of Minnesota showing the location of Figure 1B.

**B.** Bedrock geologic setting of Benton County and surrounding region (modified from Jirsa and others, 2003). Letters designate several 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; W—Watab diorite; and Z—Piezz granite.

## DESCRIPTION OF MAP UNITS

### PALEOPROTEROZOIC OR MESOPROTEROZOIC ROCKS

*Mafic intrusions for which the age is poorly known.*

Ꝑnd, Ꝑrd **Diabasic and gabbroic dikes**—Northwest- and east–northeast-trending, variably magnetic dikes inferred largely from magnetic anomalies and a few local exposures: Ꝑnd—normal magnetic polarity; Ꝑrd—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.

Ꝑp **Mafic and ultramafic intrusions**—Irregularly shaped plug- and dike-like plutons composed of serpentinized peridotite, pyroxenite, hornblendite, and hornblende- and mica-bearing diorite and gabbro. These intrusions form small aeromagnetic anomalies. $^{40}Ar/^{39}Ar$ data from a biotite grain in a similar intrusion in nearby Morrison County yielded an age of 1,791 ± 0.8 Ma (Jirsa and others, 2006). However, the date is suspect because these plutons also intruded the Foley Granite in Benton County, which is younger than 1,791 Ma.

### PALEOPROTEROZOIC INTRUSIVE ROCKS

*Intrusive units of the East-Central Minnesota Batholith (Van Schmus and others, 2000) that post-date the regional Penokean metamorphic and deformation event.*

Ꝑfg **Foley granite**—Pink to salmon-colored, biotite- and hornblende-bearing granite; medium- to coarse-grained; weakly to non-magnetic. Shallow dipping trachytoid fabric occurs locally. Unit has a U-Pb age of 1,779 ± 4 Ma (Holm and others, 2005). Intruded by small dikes of granitic porphyry and aplite.

Ꝑfm **Foley granite, magnetic phase**—Variably magnetic, pink to deep salmon-colored, variably porphyritic granite; medium- to very coarse-grained. Includes exposures in and near Granite Ledge Township. Unit has a U-Pb age of 1,774 ± 1 Ma (Holm and others, 2005). Outcrops near the west edge of the intrusion locally contain inclusions of granodiorite like that of the Reformatory Granodiorite (unit Ꝑrg). Cut locally by feldspar porphyry, aplite, pegmatite, and diabase dikes.

Ꝑwd **Watab Diorite**—Dark greenish-gray to gray, fine- to medium-grained, hornblende ferrodiorite to granodiorite. Locally cut by irregular dikes of pink granite and granitic pegmatite. Outcrops and one drill core indicate the rock locally contains steeply dipping, modal layering. Geophysical attributes are moderate to high density with a variable magnetic signature. Unit has a U-Pb age of 1,780 ± 6 Ma (Holm and others, 2005).

Ꝑrg **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, which was dated by U-Pb analysis at 1,779 ± 5 Ma (Holm and others, 2005)—equivalent with the lithologically similar Foley Granite (units Ꝑfg and Ꝑfm).

Ꝑmi **Intermediate composition, magnetic upper crustal rocks inferred from model studies** (shown only on cross-sections)—May include rocks related to the Reformatory Granodiorite (unit Ꝑrg), which has similar properties, and are interpreted to directly overlie the unit in the western part of cross section C–C'.

Ꝑlg **Little Rock pluton**—Pink to gray, coarse-grained granodiorite to diorite; outcrops north of the county contain a weak, nearly horizontal foliation. The age is unknown, but the rock is geophysically similar to the variably magnetic Glendorado pluton (unit Ꝑgg).

Ꝑgg **Glendorado pluton**—Granodiorite; based on 2 drill cores, the rock is pink, white, and black, coarse-grained, and contains biotite and steeply lineated hornblende. Variably magnetic and moderately dense. Unit has a U-Pb age of 1,788 ± 4 Ma (Holm and others, 2005).

Ꝑgr **Granite**—Pink to red, hornblende- and biotite-bearing; coarse-grained; occurs as a small intrusion northwest of the Foley Granite; mapping is based on exposures in adjacent Stearns County; age is unknown.

Ꝑgu **Granitoid rock**—Inferred from geophysical attributes of low density and magnetic expression. One of the rotary-sonic drill cores (BR-4) intersected saprolite in the adjacent Glendorado pluton that contains weathered dikes of granite and aplite, which may represent offshoots from unit Ꝑgu. Inferred beneath the Foley granite on cross sections A–A' and C–C' on the basis of model studies.

### PALEOPROTEROZOIC INTRUSIVE AND SUPRACRUSTAL ROCKS

*Intrusive and metamorphic rocks that pre-date Penokean metamorphism.*

Ꝑsz **Shear zone**—Mylonite to cataclasite, primarily of granitic protolith.

Ꝑlf **Little Falls Formation**—Gray, quartzofeldspathic biotite schist of pelitic and graywacke protolith, inferred from outcrops and drill holes in adjacent areas. One of the rotary-sonic cores (BR-1) intersected saprolite with a relict composition and fabric, indicating the rock was a fine- to medium-grained, biotite-quartz-plagioclase schist with a steeply dipping schistosity.

Ꝑsv **Schist of volcanic, volcaniclastic, and granitoid intrusive protolith**—Dark-colored rocks metamorphosed locally to greenschist facies; unit typically has high gravity and magnetic signatures. No exposures occur in the county. One of the rotary-sonic drill cores (BR-5) intersected fresh hornblende-quartz metadiorite at 37 feet (11 meters) depth. It is unclear if this is part of unit Ꝑsv, or is a boulder within the glacial sediment.

### ARCHEAN AND/OR PALEOPROTEROZOIC ROCKS

*Age is highly speculative.*

AꝐs **Sartell Gneiss**—Gray and red, medium-grained gneiss that varies from granitic to noritic composition; poorly exposed. One of the rotary-sonic cores (BR-2) intersected saprolite of medium- to coarse-grained, plagioclase-mica-quartz gneiss, with overall dioritic composition and near vertical foliation.

AꝐu **Intermediate composition, non-magnetic upper crustal rocks inferred from models studies** (shown only on cross sections)—May include metamorphic rocks related to the Sartell Gneiss and/or Little Falls Formation, which have similar properties, and are interpreted to lie directly above the unit in the northern part of cross section B–B'.

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