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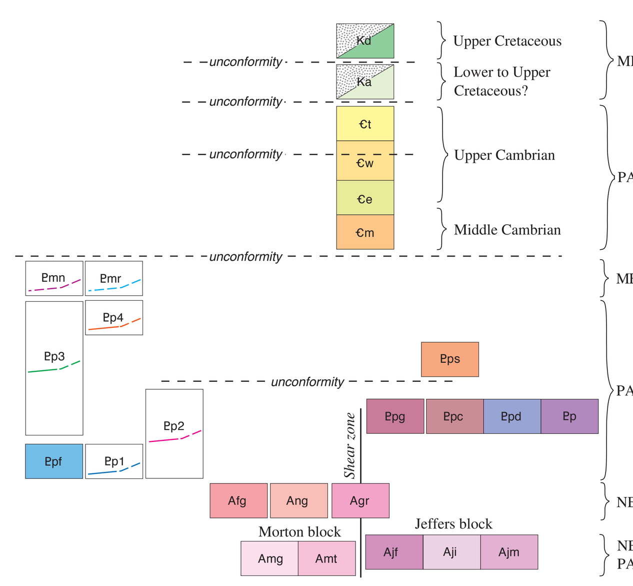
BEDROCK GEOLOGY

By

Terrence J. Boerboom and Julia R. Steenberg

2016

CORRELATION OF MAP UNITS



MAP SYMBOLS

Geologic contact—Mainly located from aeromagnetic data except where locally controlled by information from drill cores, drilling logs, and bedrock outcrops. Precambrian contacts are dashed where concealed beneath Paleozoic rocks.

Fault—Faults in Precambrian rocks are inferred from gravity and magnetic anomaly data, except where locally controlled by information from bedrock outcrops in unit Ᵽpf. Dashed where concealed beneath Paleozoic rocks.

Synform—Inferred from distribution of map units as derived from aeromagnetic data.

Strike and dip of igneous layering defined by aligned feldspar phenocrysts—Angle in degrees from horizontal; inclined, vertical.

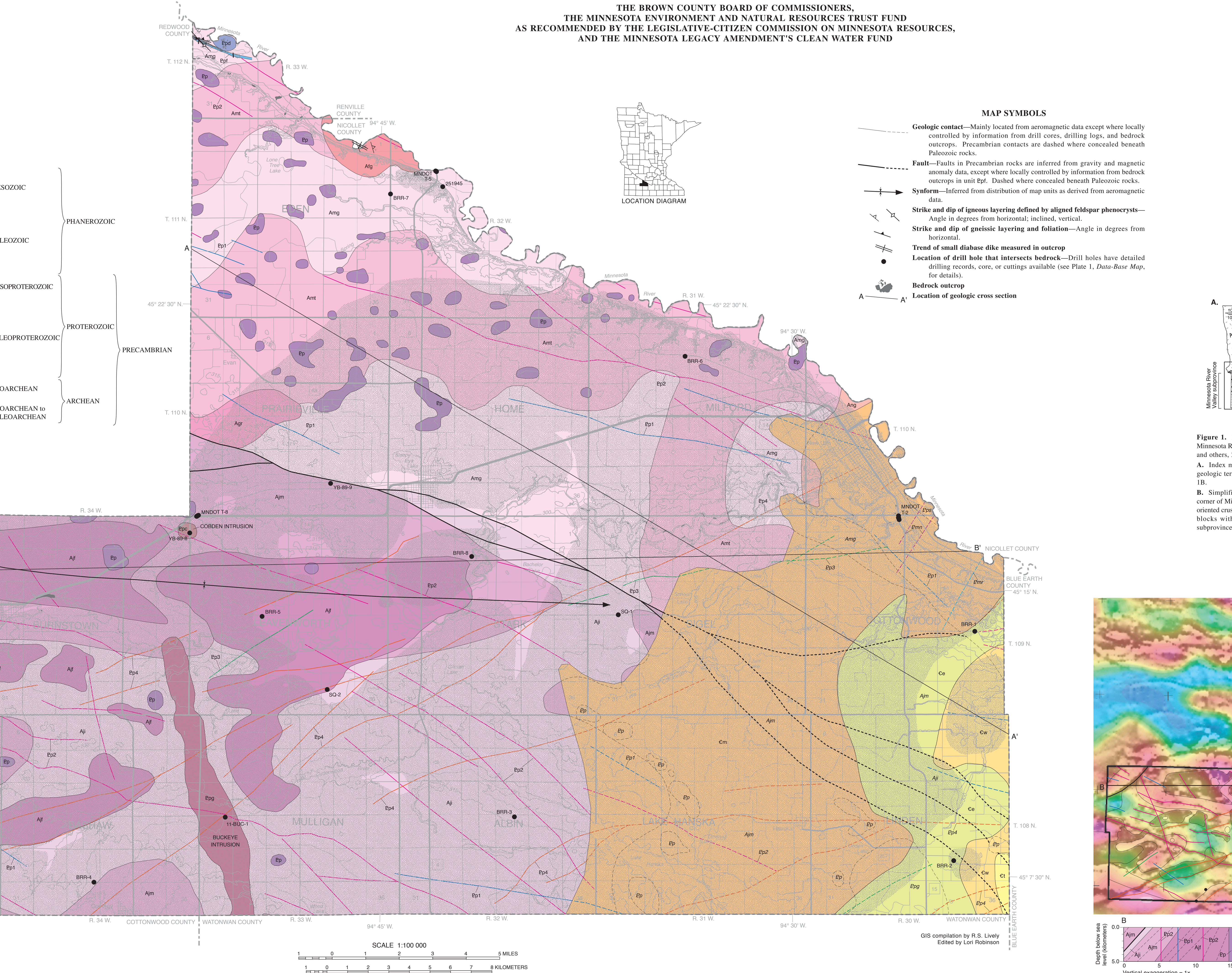
Strike and dip of gneissic layering and foliation—Angle in degrees from horizontal.

Trend of small diabase dike measured in outcrop

Location of drill hole that intersects bedrock—Drill holes have detailed drilling records, core, or cuttings available (see Plate 1, *Data-Base Map*, for details).

Bedrock outcrop

Location of geologic cross section



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

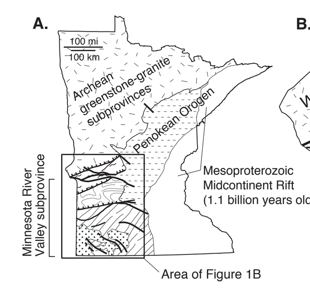
Elevation contours were derived from the U.S. Geological Survey 30-meter Digital Elevation Model (DEM) by the Minnesota Geological Survey.

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

SCALE 1:100 000

CONTOUR INTERVAL 15 METERS

GIS compilation by R.S. Lively
Edited by Lori Robinson



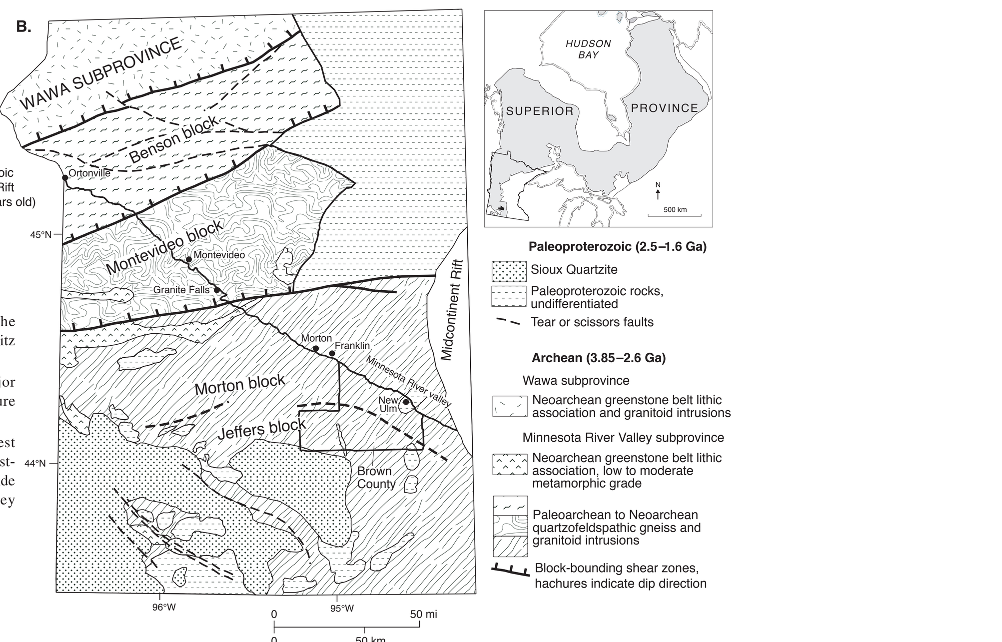


Figure 1. Bedrock geologic setting of the Minnesota River valley (modified from Schmitz and others, 2006).

A. Index map of Minnesota showing major geologic terranes; box outlines area of Figure 1B.

B. Simplified terrane map of the southwest corner of Minnesota, showing major northeast-oriented crustal-scale shear zones that subdivide blocks within the Minnesota River Valley subprovince.

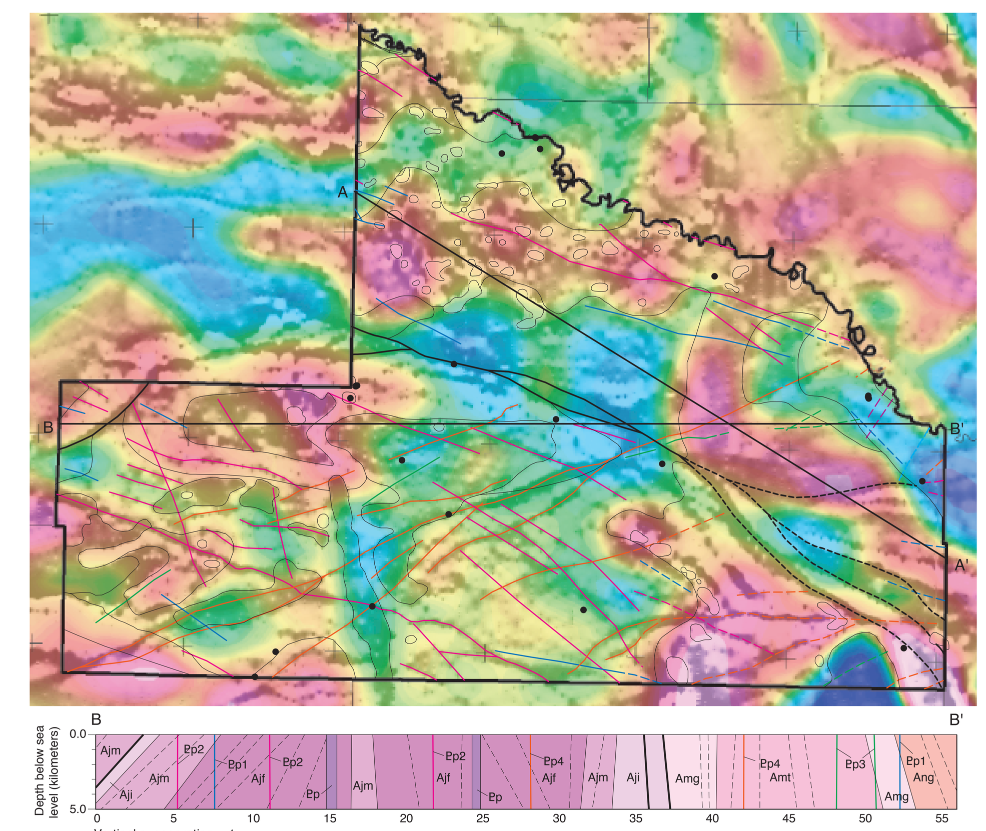


Figure 2. Map of superimposed first vertical derivative aeromagnetic data (gray scale), on second derivative of gravity data (color), showing the locations of Precambrian bedrock contacts (thin black lines) and faults (thick black lines), drill hole locations (black dots) and locations of cross sections. Dikes are shown as blue lines (reversely polarized) and purple lines (normally polarized). Dips of contacts and faults in cross-section B–B' are based principally on two-dimensional modeling of gravity and magnetic data along profiles. Dashed lines on the cross section represent geophysical contrasts that may reflect the attitudes of internal variations within the bedrock units. Scale = 1:300,000.

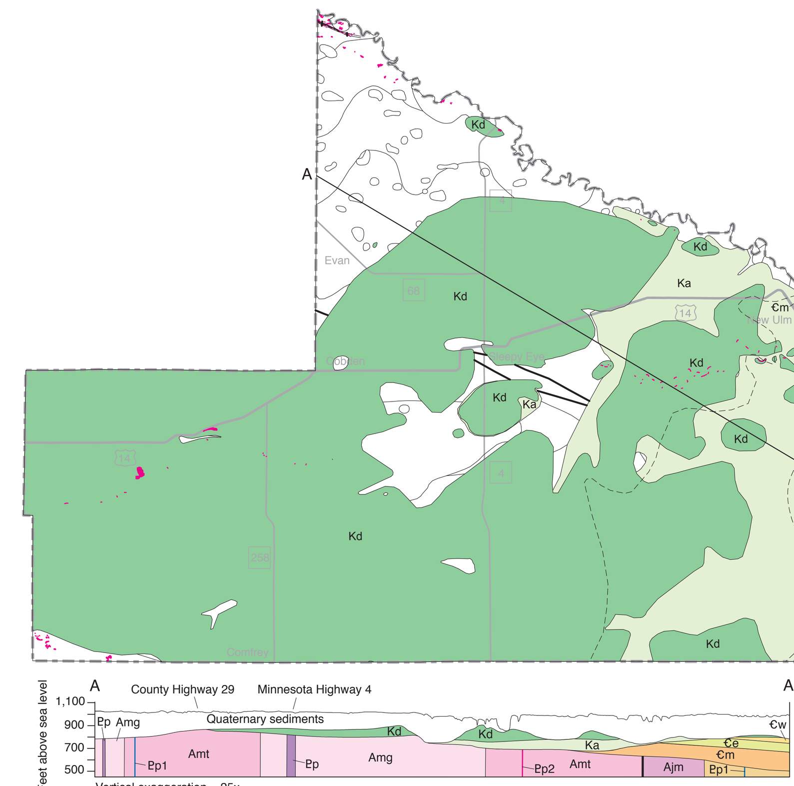


Figure 3. Geologic map and cross-section A–A' showing distribution of Cretaceous bedrock (green; units Kd and Ka), Paleozoic bedrock (units Ꞓm, Ꞓe, Ꞓw, Ꞓt), and Precambrian bedrock contacts and faults (black lines) in Brown County. The extent of Paleozoic bedrock units beneath Cretaceous rocks is depicted by dashed lines. Outcrops of both Precambrian and Cretaceous rocks are shown in magenta. Scale = 1:300,000.

INTRODUCTION

The geologic map on this plate depicts the type, distribution, and structure of the bedrock units in Brown County that are either exposed at the land surface or lie directly beneath unconsolidated Quaternary sediments of variable thickness (see Plates 3 and 4, *Surficial Geology* and *Quaternary Stratigraphy*). Most of the bedrock is covered by glacial sediment except in a corridor along the Minnesota River and some tributaries, where the overlying glacial sediment has been scoured away by river erosion, exposing the underlying bedrock. The uppermost bedrock in the northernmost tip of the county consists of a complex assemblage of Precambrian metamorphic and intrusive igneous crystalline rock types. In the southeastern part of the county, the Precambrian bedrock is covered by Paleozoic sedimentary rock layers. Both of these rock types are in turn overlain by younger Mesozoic (Cretaceous) strata, which occur over most of the county except where they have been removed by erosion. Some of these bedrock units are major reservoirs for water supply in the county and a source of industrial clay materials for various construction needs.

Characteristics of each bedrock unit are given in the description of map units. The accompanying bedrock geologic cross sections add the dimension of depth, illustrate stratigraphic relationships of the bedrock units, and show the variable thickness of the overlying Quaternary sediments. The production of the map and associated products relied on several different data sources, including outcrops, water-well records from the County Well Index (CWI), engineering 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), drill cuttings and core samples, borehole geophysical logs, aeromagnetic and gravity images, and previously published geologic maps of Brown and adjacent counties (Southwick, 2002; Jirsa and others, 2011, 2015; Mossler and Chandler, 2012; Steenberg, 2012). The somewhat irregular distribution and density of data can be seen on Plate 1, *Data-Base Map*, and this should be considered when assessing the reliability of the map at any particular location. Areas with a high density of bedrock control points are more likely to have accurate interpretation of the bedrock geology, whereas those areas with widely spaced control points may be less reliable and inappropriate for site-specific needs.

GEOLOGIC SETTING AND HISTORY

PRECAMBRIAN BEDROCK

Brown County is located near the southern edge of the Canadian Shield, which forms the ancient center of North America, within the Minnesota River Valley subprovince of the Superior Province (Fig. 1). The dominant Precambrian bedrock in Brown County ranges from Archean (approximately 3,500 to 2,600 million years ago, or Ma) to Paleoproterozoic (approximately 2,100 to 1,700 Ma) in age, and includes some rocks of Mesoproterozoic (approximately 1,100 Ma) age.

With the exception of some areas in the Minnesota River valley at the north edge of the county, the Precambrian bedrock is entirely covered by younger Paleozoic and Mesozoic sedimentary rocks, and by a thick cover of glaciogenic sediment of Quaternary age. As a result, the distribution of the Precambrian bedrock units is mostly inferred from aeromagnetic and gravity geophysical data, by comparing the geophysical signatures of areas where the bedrock is buried with areas where bedrock and drilling control exist (Fig. 2).

The Archean Morton Gneiss, the oldest known rock type in Brown County, is exposed in the Minnesota River valley in the northern part of Brown County. These high-grade Archean gneissic rocks have undergone multiple generations of intrusion and metamorphism, resulting in a series of complexly interlayered rock types that are difficult to portray on a geologic map of this scale, even where they are exposed at the surface.

Paleoproterozoic bedrock consists of multiple generations of mafic diabase dikes, such as the reversely-polarized Franklin dikes, which are exposed in outcrops at the northwest part of the county. Other dikes of varied orientations of both normal and reverse polarity were identified from linear aeromagnetic anomaly patterns. A granitic pluton of Paleoproterozoic age was identified by a U-Pb age date. Others were delineated by their distinctive geophysical signatures. Other Paleoproterozoic units include the Sioux Quartzite, which was delineated on the basis of its subdued aeromagnetic anomaly pattern combined with mapped outcrops in the southwest part of the county, and small intermediate to ultramafic intrusions that were generally demarcated by high amplitude aeromagnetic anomalies.

Linear, northwest-oriented aeromagnetic lineaments at the eastern edge of the county are interpreted to be produced by Mesoproterozoic diabase dikes emplaced outside of the main axis of the Midcontinent Rift.

SAPROLITE

Saprolite is a term used for in-place chemically weathered residuum of preexisting bedrock by meteoric waters, converting the primary minerals in the rock, such as feldspar, to various green and white clay minerals, largely kaolinite. Where weathering is incomplete, these clays are commonly mixed with angular residual crystals that are more resistant to the weathering processes, mostly quartz and potassium feldspar. In general, clay content is largest at the top of the weathering profile and the proportion of residual grains increases with depth, grading into fresh rock below. The resulting blanket of saprolite, commonly referred to as "decomposed granite," typically varies in thickness from 10 to 100 feet (3 to 30 meters), but may be much thicker.

In Brown County, as in most of Minnesota, the upper portion of the Precambrian bedrock is mantled by a variably thick rind of saprolite. Although this weathering may have occurred at several different times, the most recent interval of deep weathering occurred before or during deposition of Cretaceous sedimentary rocks (around 90 to approximately 113 Ma), as indicated by saprolites that lie below the Cretaceous strata, and by beds in the Cretaceous materials that are composed of reworked saprolite (Setterholm and others, 1989). Because weathering requires interaction with water, the degree of weathering in impermeable crystalline bedrock (for example granite and gneiss) occurs not only from the surface downward, but also from both horizontal and vertical fractures into the bedrock. Thus weathering is controlled largely by the degree to which the bedrock is fractured. Other factors that determine the susceptibility of bedrock to weathering include the chemical composition of the rock and the amount of anisotropic fabric development, such as metamorphic foliation and compositional layering (for example Setterholm and others, 1989). As weathering proceeds into the bedrock from horizontal and vertical fractures, rounded "nuggets" of fresh, unweathered rock, referred to as corestones, are commonly left behind. Many of the outcrops of Morton Gneiss in the northwestern part of Brown County exhibit this characteristic rounded shape as a result of the clay-weathered saprolite cap having been eroded away by formerly higher water levels in glacial River Warren.

Typically the uppermost parts of saprolite horizons are the most weathered, and original igneous and metamorphic fabrics are not discernible. In these zones, even the protolith (the original, pre-weathering rock type) cannot be established with certainty. Progressing downward into less weathered horizons, primary rock fabrics are commonly preserved, despite partial replacement of feldspar and other minerals by various clays. Based on scant drill hole data, the saprolite in Brown County varies in thickness from a few feet to hundreds of feet and can vary greatly over short distances. Saprolite is not mapped as a separate unit here because: 1. It typically is gradational with underlying, less weathered bedrock; 2. It appears to be present nearly everywhere in the county, except in small localized areas where it presumably was partially removed by erosion; and 3. Saprolite is difficult to distinguish in most drilling records from glacial sediments and Cretaceous strata. The low-grade kaolin found in the saprolite is easily extracted from the ground, and has been used for a variety of products including bricks and as an additive for manufacturing cement. The clay is desirable for cement making because its low alkali content minimizes the generation of highly alkaline waste products.

PALEOZOIC BEDROCK

The Paleozoic rocks in Brown County are characterized by thin, widespread layers of sandstone, siltstone, shale, and carbonate deposited in shallow seas during the Cambrian Period of the Paleozoic Era from about 500 to 497 Ma. Sandstone and siltstone dominate these formations and shale and carbonate occur only as relatively thin layers. The geology of the Paleozoic rocks is based largely on descriptions from about 100 drillers' logs from water well records in the County Well Index (CWI), and where available, cuttings and geophysical logs from municipal and other deep wells (see Plate 1, *Data-Base Map*). The distribution of the Paleozoic rock units is primarily influenced by the east to southeasterly regional dip of the Paleozoic bedrock reflected on the map by a pattern of progressively younger formations to the southeast. Paleozoic rocks to the west have been removed by erosion.

MESOZOIC BEDROCK

The Cretaceous sedimentary rocks (units Kd, Ka, shown collectively by pattern), which locally cover Precambrian and Paleozoic rocks throughout the county, consist of poorly lithified mudstone and sandstone (see Fig. 3 for the full coverage of these rocks). They were likely laid down continuously across the area, but subsequently eroded to produce scattered remnants. The distribution of these rocks is based on geologic interpretations of lithologic descriptions provided by well drillers from nearly 600 wells. The mapped distribution of these units is much more speculative than for other map units because of the presence of profound unconformities bounding these strata, and because information from drillers' logs alone is typically inadequate to consistently distinguish these strata from quartz-rich Quaternary sand, organic-rich Quaternary lake sediments, or saprolite on top of Precambrian granitic rocks.

The Mesozoic and Paleozoic geologic formations are very thin in relation to their areal extent and would be too thin to show on a cross section if no vertical exaggeration were used; thus the vertical scale on cross-section A–A' (Fig. 3) is greatly exaggerated (25x). As a result, the slopes of the bedrock contacts, land surface, and bedrock topography appear to be much steeper than they actually are.

HYDROSTRATIGRAPHY

Stratified Mesozoic and Paleozoic sedimentary bedrock is a significant source of groundwater in Brown County. This map and associated products, such as the bedrock Digital Elevation Models (Plate 5), provide a three-dimensional depiction of the rock properties that control flow in these water-bearing layers. Such characteristics of the bedrock are called hydrostratigraphic properties. The hydrostratigraphic properties shown in the stratigraphic column (Fig. 4) distinguish layers that have relatively high permeability (easily transmitting water), versus layers that have lower permeability (relatively more difficult to transmit water). The high permeability layers are potential aquifers, able to store and yield water in usable quantities in most places. The low permeability layers are potential aquitards that retard flow, hydraulically separating the aquifer layers from one another in many places. In Brown County, most bedrock aquifers are layers dominated by relatively coarse-grained sandstone such as the Mt. Simon Sandstone. Aquitards are composed mostly of finer-grained sandstone, siltstone, and shale and have a much lower permeability, such as the Eau Claire Formation. However, layers designated as aquifers can locally contain low permeability strata that serve as internal aquitards, including parts of the upper Mt. Simon Sandstone. Conversely, aquitards that have very low permeability in a vertical direction commonly contain horizontal fractures that are conductive enough to yield large quantities of water. Horizontal as well as vertical fractures are more common when bedrock layers are at or near the bedrock surface (unconfined by overlying strata). As a result, aquitards in such conditions may be especially conductive and have a diminished ability to retard water flow to underlying aquifers. This generalized characterization for Brown County is based on hydrogeologic reports by Runkel and others (2003, 2006a, b) and unpublished borehole and core data collected by the Minnesota Geological Survey in the general Twin Cities metropolitan area.

Little is known about the hydrostratigraphic properties of the Cretaceous units. However, the Dakota Formation (unit Kd) is known to yield a significant amount of water to domestic wells and is therefore considered an aquifer. The finer-grained unnamed unit (Ka) yields significantly less water to domestic wells and is therefore considered an aquitard. The relatively hard Precambrian crystalline bedrock locally supplies water to domestic wells in northwestern Brown County and is likely derived largely from water-bearing fractures within the Precambrian rock. Many of these wells are also open to a small portion of the Quaternary sediments above and receive water from both sources. Hydrogeologic data and interpretations by the Minnesota Department of Natural Resources as part B of the Brown County Geologic Atlas may result in modifications to the hydrostratigraphic characterization presented here. Furthermore, the well construction regulations of the Minnesota Department of Health may not correspond precisely in designation of aquifers and aquitards.

DESCRIPTION OF MAP UNITS

MESOZOIC ROCKS

Kd **Dakota Formation (Upper Cretaceous; color only on Fig. 3)**—Interbedded sandstone, siltstone, and mudstone. Sandstone is quartzose and can be white, gray, brown, or orange in color, and have clasts of white kaolinite, biotite, and black lignite. Sand grains are fine- to coarse-grained and angular to subrounded. It is generally friable, with minor iron oxide and calcite cement. Mudstone is dark gray to brown, mostly non-calcareous, with light brown to white silty laminations. Black lignite plant fragments, pisoid concretionary grains, and well-cemented siderite concretions are commonly interspersed within the sandstone, siltstone, and mudstone. The formation is as thick as 275 feet (84 meters) and unconformably overlies the undifferentiated unit (Ka), Paleozoic bedrock, and Precambrian crystalline rock at elevations between 700 and 1,150 feet (213 to 351 meters) above sea level. This unit is interpreted to represent the easternmost extent of a large, nearly continuous subcrop area of strata generally correlative with the Dakota Formation (Setterholm, 1990). These rocks were likely deposited as sediment in a fluvially-dominated delta plain on the shallow, eastern margin of the Western Interior Seaway that covered much of central North America during the Late Cretaceous Epoch. This unit contains a rich and diverse assemblage of palynomorphs with taxa that are considered to be no older than Late Cretaceous (late Cenomanian) in age (Hu and others, 2008).

Ka **Undifferentiated (Lower to Upper Cretaceous? Color only on Fig. 3)**—Red-brown to pale olive mudstone, siltstone, and interbedded yellow-gray, very fine- to medium-grained sandstone containing small flakes of black lignite. Generally friable, but does contain iron-rich concretions and intergranular carbonate and pyrite cement. Faint horizontal laminations and centimeter-scale bedding are present in some intervals; others are very uniform and massive; and some are convoluted by soft sediment deformation. The unit is as thick as 200 feet (61 meters) in Brown County. It unconformably overlies Paleozoic bedrock and Precambrian crystalline rock units at elevations between 600 and 900 feet (183 to 274 meters) above sea level. The thickest sections appear to be best preserved in topographic lows that were present prior to deposition of the unit, mainly between the Paleozoic strata to the east and the Precambrian basement to the west. This unit commonly contains a larger proportion of coarse angular quartz grains where it overlies Precambrian basement rocks, due to the availability of residual quartz grains within the weathered Precambrian source. Despite repeated analysis for pollen from drill cores in the region, only a single datable gymnospermous pollen grain and a dinoflagellate cyst have been extracted from this unit, in McLeod County to the north. They suggest a late Albian to Cenomanian age (Ravn, unpub. data, 2009).

PALEOZOIC ROCKS

Ꞓt **Tunnel City Group (Upper Cambrian)**—Variegated sandstone, siltstone, and shale with subordinate beds of dolostone. Present only in the southeast corner of Brown County, where it is the uppermost bedrock. It exceeds 100 feet (30 meters) in thickness in adjacent counties, but is eroded to a maximum thickness of only 20 feet (6 meters) in Brown County. The sandstone is yellowish-gray to green, very fine- to fine-grained, quartzose, feldspathic, and glauconite-rich. It is commonly interbedded with greenish-gray shale beds. The dolostone is light tan to pink, contains sandstone intraclasts, and becomes more abundant toward the base of the formation. Glauconite is present throughout, but is most abundant in the basal part of the formation.

Ꞓw **Wonewoc Sandstone (Upper Cambrian)**—Fine- to coarse-grained, moderately sorted, friable, white to tan, quartzose sandstone with white linguliform brachiopod shells. The lower portion of the formation is typically finer-grained and better sorted. Glauconite is present in the upper part of the formation and absent in the remainder. The formation is present in the southeastern portion of Brown County. The maximum thickness of the Wonewoc Sandstone is 55 feet (17 meters).

Ꞓe **Eau Claire Formation (Middle to Upper Cambrian)**—Variegated light green, feldspathic siltstone, shale, and very fine- to fine-grained sandstone with subordinate light pink dolomite. The shale is dominantly green, white, and red. The sandstone is white to tan to pink and well-cemented with carbonate. Glauconite and white to brown linguliform brachiopod shells are present throughout the formation and are most commonly associated with the dolostone beds. The maximum thickness of the Eau Claire Formation is 75 feet (23 meters) thick. This formation is present in the southeast portion of Brown County. The contact with the underlying Mt. Simon Sandstone is transitional, but defined at the first medium- to coarse-grained sandstone bed.

Ꞓm **Mt. Simon Sandstone (Middle Cambrian)**—Fine- to coarse-grained, well rounded, white to light gray to pale yellowish-brown, quartzose sandstone with thin interbeds of white and green feldspathic shale and siltstone. Interbeds of shale and siltstone are common in the upper one-third of the formation where it is transitional with the Eau Claire Formation. The sandstone is generally very friable to poorly cemented. Pebbles of vein quartz are present near its base and scattered white linguliform brachiopod shells are common in the upper one-third of the formation. The Mt. Simon Sandstone is less than 200 feet (61 meters) thick. The formation is present in the eastern part of Brown County.

PROTEROZOIC ROCKS

Note that where overlain by Paleozoic strata, Precambrian contacts, faults, and dikes are dashed, and unit labels are italicized.

Mesoproterozoic rocks—The Mesoproterozoic Midcontinent Rift formed approximately 1,100 million years ago by extension of the earth's crust along a north–south axis that extends from beneath Lake Superior, along the present-day Minnesota–Wisconsin border, and southwest to as far as Kansas. The main axis of the rift lies east of Brown County (Fig. 1) and is filled with as much as 19 miles (30 kilometers) of mostly mafic volcanic rocks that were extruded onto the surface as lava flows, and later covered with a thick sequence of sandstone-dominated sedimentary rocks. During crustal extension, swarms of mainly rift-parallel mafic dikes were emplaced into the crust outside of the main rift axis. One of these dike swarms, demarcated by prominent linear anomalies on aeromagnetic maps, extends into Brown County but is located mainly to the east. As typical of the Midcontinent Rift magmatism, some of the dikes are reversely polarized and appear as negative aeromagnetic anomalies, and some of the dikes are normally polarized and appear as positive aeromagnetic anomalies. The Midcontinent Rift is well documented in several publications, including Hinze and others (1997).

Ᵽmn **Diabase dike, normally polarized**—Oriented at approximately 20°.

Ᵽmr **Diabase dike, reversely polarized**—Oriented at approximately 20°.

Paleoproterozoic rocks—Most Paleoproterozoic rocks in Minnesota formed in the east-central part of the state as a product of volcanism, sedimentation, and metamorphism during multiple episodes of rifting and collision associated with the approximately 1,880 to 1,830 Ma Penokean Orogeny (Fig. 1; for example Schulz and Cannon, 2007, and references therein). Rocks of the Penokean Orogen were subsequently intruded by numerous granitoid intrusions that collectively form the east-central Minnesota batholith (Holm and others, 2005). However, within the Minnesota River Valley subprovince (Fig. 1), the known occurrences of Paleoproterozoic rocks are minor, and restricted to mafic dikes and discrete mafic to felsic plutons emplaced into older Archean crust (for example Jirsa and others, 2011), and to the Sioux Quartzite. In Brown County, Paleoproterozoic rocks are represented by granitic plutons such as the Buckeye intrusion (part of unit Ᵽpg), by northwest-trending mafic dikes such as the Franklin diabase dikes (unit Ᵽpf), and likely by small, plug-like mafic intrusions (units Ᵽpc, Ᵽpd, Ᵽp). Other mafic dikes (units Ᵽp1, Ᵽp2, Ᵽp3, Ᵽp4) mapped on the basis of aeromagnetic lineaments that are of varied orientations, are likely Paleoproterozoic in age.

The Sioux Quartzite is interpreted to have formed between 1,750 and 1,630 Ma (Holm and others, 1998) as cross-bedded quartz arenite with thin interbedded mudstone deposited on top of older Paleoproterozoic and Archean bedrock, mainly by fluvial braided streams and possibly in shallow marine environments in the upper portion. The mineralogic, sedimentologic, and structural aspects of the Sioux Quartzite are well documented in several publications, for example Ojakangas and Weber (1984), and references therein.

Ᵽp4 **Diabase dike, reversely polarized, northeast-trending**—Age is uncertain, but based on cross-cutting linear aeromagnetic anomalies, at least some of the dikes in the trend cross-cut the approximately 1,780 Ma Paleoproterozoic Buckeye intrusion (unit Ᵽpg). Aeromagnetic data also indicate that some dikes of this orientation may postdate the Sioux Quartzite in Brown County and in Jackson County to the south.

Ᵽps **Sioux Quartzite**—Pink to maroon, vitreous, medium- to coarse-grained; protolith of quartz arenite sandstone. Contains minor, thin layers of conglomerate and well indurated mudstone and siltstone. This unit is exposed at the land surface in or near two areas of the county. In the southwest, there are several exposures of quartzite that lie at the northern margin of a larger outcrop area; these are part of what is informally termed the Cottonwood basin (for example Southwick and Mossler, 1984). Based on studies of drill cores and outcrops, the total estimated thickness of the quartzite in this basin is 1,600 feet (490 meters; Chandler and Morey, 1992). Just east of New Ulm in Nicollet County, there are outcrops of basal conglomerate as well as quarries developed in the Sioux Quartzite (Mossler and Chandler, 2012) in the Minnesota River valley. This quartzite occurrence is inferred to extend slightly west into Brown County in the subsurface beneath Cretaceous and Paleozoic strata.

Ᵽp3 **Diabase dike, normally polarized, northeast-trending**—Defined in Brown County by only weak and relatively short, linear, positive aeromagnetic anomalies, but 20 miles (32 kilometers) to the south in Jackson and Martin Counties, aeromagnetic data indicate that there are larger dikes of this orientation that postdate the Sioux Quartzite. Forty miles (64 kilometers) to the northwest near Granite Falls in Yellow Medicine County, a small, northeast-trending dike of unknown polarity has an age of 1,878 ± 8 Ma (Chamberlain, unpub. data, 2014). The relationship of both of those dike sets to this set in Brown County is not known, however, this may indicate that the dikes included in this unit are part of more than one swarm.

Ᵽp2 **Diabase dike, reversely polarized, northwest-trending**—Defined by linear, negative aeromagnetic anomalies. Based on cross-cutting aeromagnetic anomaly patterns, at least some of the dikes in this trend postdate the approximately 1,780 Ma Buckeye intrusion (unit Ᵽpg), but others may be related to the Franklin dikes and in turn the approximately 2,100 Ma Kenora–Kabetogama dike swarm. Just south of Brown County, linear magnetic lows ascribed to this dike swarm show a subdued expression where they cross the Sioux Quartzite, implying they are buried beneath it.

Ᵽpg **Granite**—Inferred from well-defined aeromagnetic lows with magnetic high rims, and corresponding negative gravity anomalies, both of which truncate the geophysical signatures of the surrounding gneissic rocks. A drill core sample (drill hole 11-BUC-1) from the north–south elongate body in southwestern Brown County informally referred to as the Buckeye intrusion, yielded a $^{207}Pb/^{206}Pb$ zircon age of 1,782.31 ± 0.64 Ma (Schmitz, 2014). This age is similar to other intrusions in east-central Minnesota (Holm and others, 2005) and in southwestern Minnesota (Southwick and others, 1994) that range in age from 1,800 to 1,772 Ma, and are associated with Yavapai-interval orogenesis. One of the granites included in this unit is buried beneath Paleozoic and Cretaceous strata, along the southeast border of the county.

Ᵽpc **Cobden intrusion**—Hornblende gabbronorite, dark greenish-gray to black, medium-grained; exhibits a strong trachytoid foliation via flow-aligned plagioclase laths. A typical example of this unit is composed of 63 percent plagioclase, 17 percent subpoikilitic hornblende that forms thick rims over pyroxene, 6 percent hypersthene, 4 percent augite, 3 percent each of Fe-Ti oxide minerals, biotite, and quartz, and less than 1 percent each of apatite and secondary actinolite, chlorite, carbonate, and epidote. This intrusion creates a small, sharp, positive magnetic anomaly. See Southwick and others (1993) for the geochemical composition of this unit.

Ᵽpd **Hornblende quartz monzodiorite to hornblende-augite diorite**—Greenish-pink to dark green, medium- to coarse-grained. Composed dominantly of varied proportions of plagioclase, hornblende, augite, alkali feldspar, quartz, and biotite and minor amounts of apatite and epidote. The more felsic end-member has granophyre in the mesostasis, and phenocrysts of augite up to 1 centimeter wide that are rimmed by hornblende and variably replaced by a mosaic of secondary chlorite and calcite. It also contains local miariolitic cavities up to 3 centimeters in size that are lined with crystalline adularia and quartz and variably filled with calcite. The more mafic end-member is similar but contains poikilitic biotite, minor altered olivine, and less alkali feldspar and quartz. The extent of this intrusion as shown in the northern corner of the county is based on aeromagnetic data, but within that area there are outcrops of granitic gneiss too small to map at this scale, which indicate that the intrusion either contains inclusions or forms an irregular intrusive network.

Ᵽp **Ultramafic to intermediate composition plug-like intrusion**—Unit was mapped on the basis of small, sharp, positive magnetic anomalies that are similar to the anomalies created by units Ᵽmc and Ᵽmd, and also to anomalies in east-central Minnesota that range from ultramafic pyroxene-olivine hornblendite to gabbronorite, diorite, and granodiorite (for example Boerboom, 2014).

Ᵽp1 **Diabase dike, normally polarized, northwest-trending**—Defined by linear, positive aeromagnetic anomalies. Age is uncertain, but based on trend may be related to the approximately 2,100 Ma Kenora–Kabetogama dike swarm (Southwick and Day, 1983).

Ᵽpf **Franklin diabase dike**—Gray, medium-grained, intergranular-subprismatic, reversely polarized (Chandler, unpub. data). Composed of approximately 60 percent variably sericite-altered and zoned plagioclase, 35 percent subprismatic to locally subophitic augite that is commonly cored by pigeonite, 3 percent irregular-suboctahedral magnetite, 2 percent hornblende and actinolite that generally rims augite, and minor chlorite and apatite. Dikes merge and split along their lengths, with slivers of Morton Gneiss between; where merged, the dike is 450 feet (137 meters) in width. This diabase was emplaced at 2,067.3 ± 1 Ma (Schmitz and others, 2006), and may be related to the approximately 2,100 Ma Kenora–Kabetogama dike swarm, a large swarm that spans the Archean Superior Province from southern Minnesota into southern Ontario (Southwick and Day, 1983).

ARCHEAN ROCKS

Based on geophysical data, primarily aeromagnetic maps, the Minnesota River Valley subprovince has been interpreted to comprise distinct subterranes referred to as *blocks*, separated by major shear zones. From north to south, these subdivisions have been termed the Benson block, the Montevideo block, the Morton block, and the Jeffers block (Fig. 1; Southwick and Chandler, 1996). Brown County overlies the southeastern margin of the Morton Block and much of the Jeffers block, separated by what is interpreted from aeromagnetic data to be a shear zone that splays southeast into several subsidiary shear zones. The Morton block in Brown County is characterized by relatively subdued aeromagnetic patterns punctured by a multitude of younger Paleoproterozoic mafic intrusions, whereas the Jeffers block is characterized by an overall slightly higher aeromagnetic intensity that includes several linear, positive magnetic anomalies interpreted to represent mafic metamorphosed volcanic rocks and/or sills that are an integral part of the overall gneissic character of the bedrock. Geochronologic studies on the Morton Gneiss to the west of Brown County show that the gneiss has undergone multiple episodes of intrusion and metamorphism that led to the complexity of the Morton Gneiss as seen today. These studies have shown that some of the phases are more than 3.5 billion years old, overprinted by metamorphic events at approximately 3.4 Ga, 3.1 Ga, and 2.6 Ga (billion years ago; Bickford and others, 2006; Schmitz and others, 2006).

Late- to post-kinematic granitic plutons, emplaced at approximately 2.6 Ga, mark the end of Archean deformation and crustal accretion in the Minnesota River Valley subprovince (Bickford and others, 2006; Schmitz and others, 2006). In Brown County, these "stitching" plutons are represented by the Fort Ridgely Granite (unit Afg) and possibly the granite body near New Ulm (unit Ang).

Geochronologic data from the Jeffers block are limited to one age date from a drill core located just south of Brown County, where tonalitic gneiss was dated at approximately 2.6 Ga (Southwick and others, 1994). It is unknown whether this is representative of the Jeffers block as a whole or whether there are other older components within this block similar to those observed in the Morton block to the north. The paucity of geochronologic data from the Jeffers block is a direct result of the lack of exposed bedrock.

Afg **Fort Ridgely Granite**—Salmon pink to gray, coarse-grained, porphyritic-trachytoid biotite granite. Blocky-rectangular microcline phenocrysts up to 1 inch (2.5 centimeters) in length vary in abundance due to flow segregation; less porphyritic areas tend to be grayer in color. Age is unknown but inferred to be Neoarchean based on the similarity of textures to other porphyritic granites exposed along the Minnesota River valley as far north and west as Ortonville, Big Stone County, which have U-Pb zircon ages from 2,590 to 2,604 Ma (for example Bickford and others, 2006; Schmitz and others, 2006).

Ang **Granite near New Ulm**—Dusky red, coarse-grained, porphyritic-trachytoid biotite granite. Contains phenocrysts of microcline up to 2 inches (5 centimeters) in length; biotite is altered to green chlorite and quartz in the mesostasis is recrystallized and mortar-textured. Outcrops contain deformed white quartz veins that pinch and swell. Exposed in the Minnesota River valley floor just east of New Ulm, where it is unconformably overlain by basal conglomerate of the Sioux Quartzite; the deep red color is likely the product of weathering beneath the quartzite. This granite is inferred to be Archean in age, based on general similarity in texture to the Fort Ridgely granite and to other late Archean porphyritic granites exposed in the Minnesota River valley to the northwest near Ortonville. The extent is defined by a moderate gravity low and subdued positive aeromagnetic anomaly patterns.

Agr **Granitoid rock, undifferentiated**—Mapped solely from geophysical expression on the basis of relatively low magnetic and gravity anomaly patterns. The bulk of this unit occurs to the west in Redwood County.

Morton block

Amg **Morton Gneiss—Felsic composition**—Defined by an irregular aeromagnetic anomaly pattern that corresponds with a moderate gravity low. This unit is dominated by a paleosome of biotite monzonite to tonalite orthogneiss with amphibolitic rafts, and a granitoid neosome that occurs as irregular stringers and dikes that commonly contain megacrystic orthoclase. Continues to the north and west into Renville and Redwood Counties, where it is mapped as granite-rich migmatitic gneiss (Jirsa and others, 2013, 2015), and to the northeast into Nicollet County (Mossler and Chandler, 2012).

Amt **Morton Gneiss—Intermediate composition**—The aeromagnetic anomaly pattern is generally similar to that of unit Amg, and aeromagnetic trends cross the boundary between the two units; however, this unit is characterized by moderate positive gravity anomalies. This unit is interpreted to be composed primarily of tonalitic gneiss with a significant proportion of amphibolite rafts and layers.

Jeffers block

Ajf **Felsic to intermediate gneiss**—Inferred from subdued aeromagnetic and gravity signatures to be slightly more felsic than unit Aji. Intersected by two drill cores (BRR-5 and SQ-2), which both intersect grayish-pink, weakly gneissic-layered biotite granodiorite to biotite-quartz monzodiorite. The layering and accompanying weak foliation in drill core SQ-2 has a shallow (10° to 15°) dip.

Aji **Intermediate gneiss**—Inferred entirely from geophysical signatures; the gravity signature is similar to unit Ajf but is marked by a moderate, positive aeromagnetic signature.

Ajm **Intermediate to mafic gneiss**—Inferred from geophysical evidence; delineated by moderately positive aeromagnetic and gravity signatures; anomalies tend to be more linear, possibly a reflection of rocks with a protolith of mafic volcanic or intrusive rock types. A drill core from just south of Brown County is composed of pinkish-gray, granoblastic, massive to weakly gneissic-layered and foliated biotite-hornblende tonalite with scattered dark gray enclaves of sphene- and apatite-rich mesocratic granodiorite; a sample from that drill core yielded a U-Pb zircon age of 2,624 ± 56 Ma (Southwick and others, 1994).

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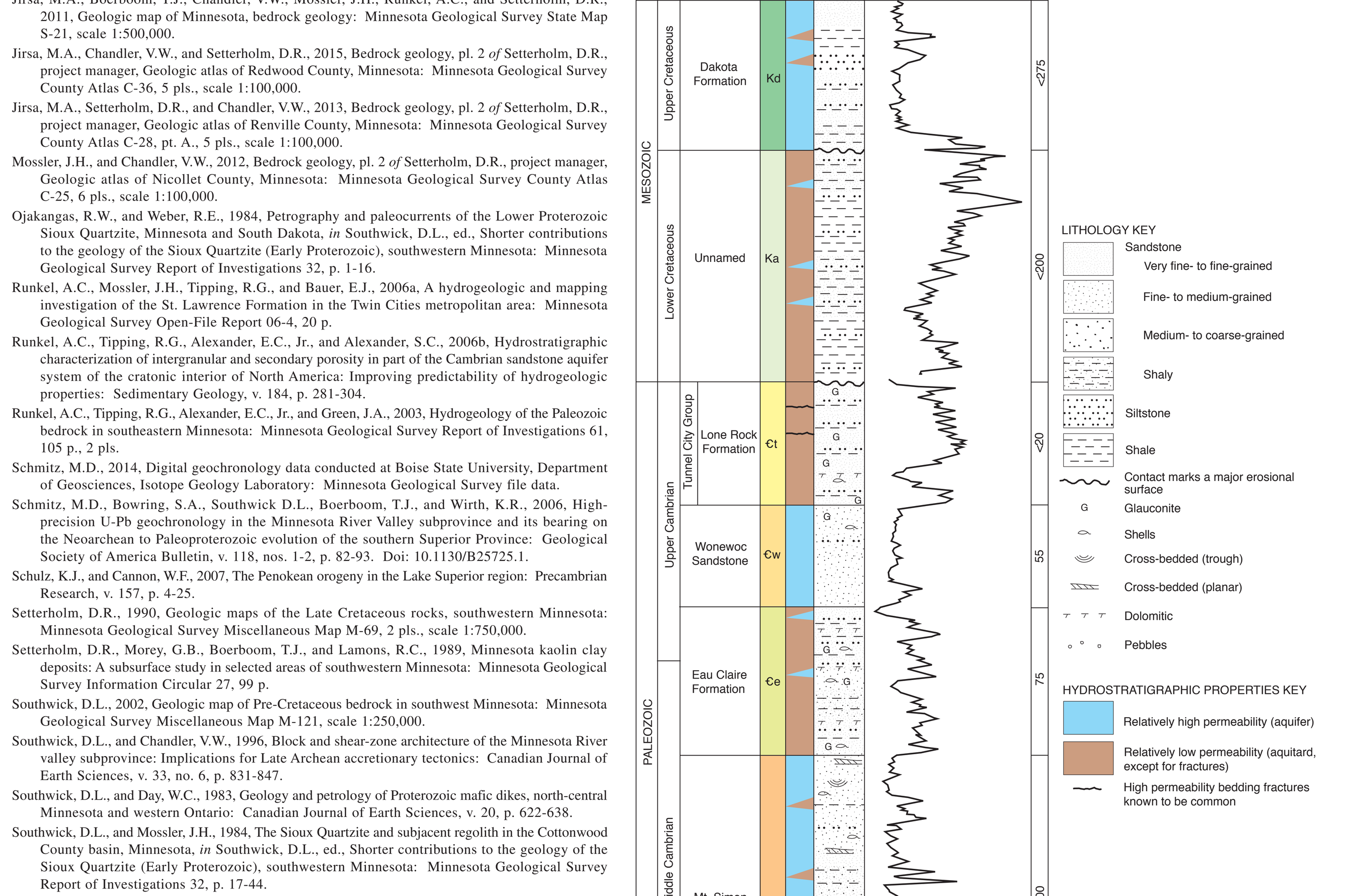

Figure 4. Generalized stratigraphic column depicting the lithology, thickness, vertical succession, age, and hydrostratigraphic properties for the Phanerozoic units shown on the map. The gamma log is a compilation of borehole geophysical logs on file at the Minnesota Geological Survey: CWI unique numbers 760651 and 760689.