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AS RECOMMENDED BY THE LEGISLATIVE-CITIZEN COMMISSION ON MINNESOTA RESOURCES

BEDROCK GEOLOGY

By

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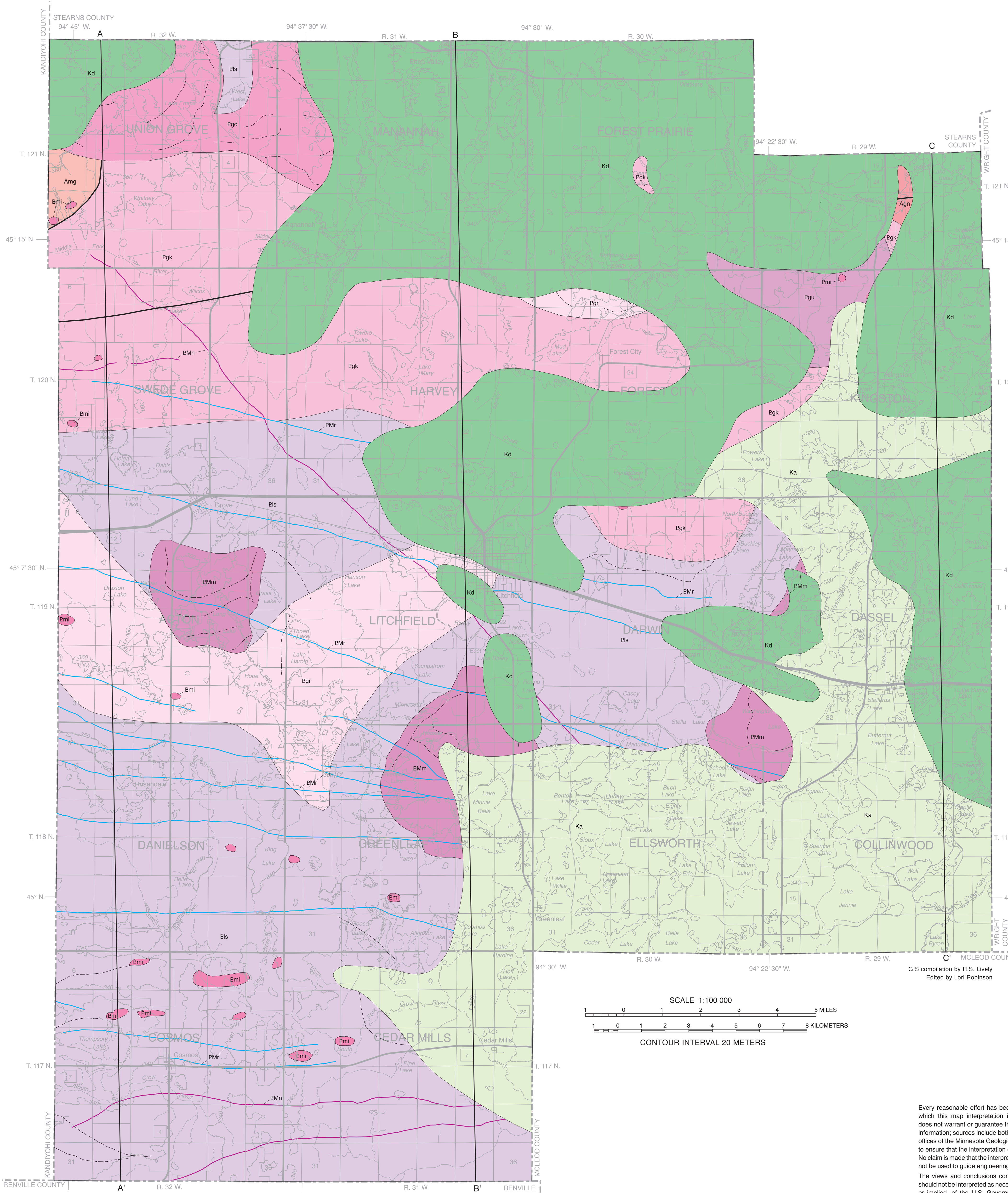
2015



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

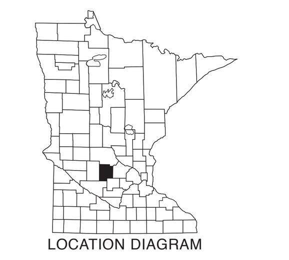
SCALE 1:100 000

CONTOUR INTERVAL 20 METERS

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

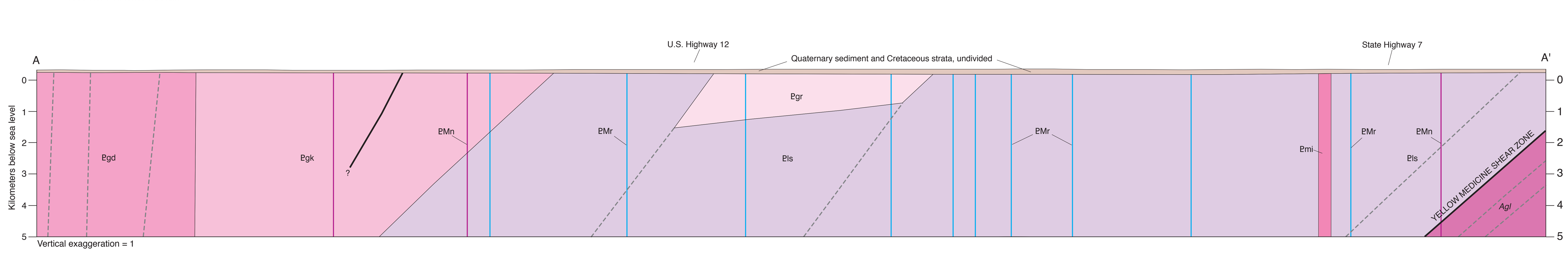


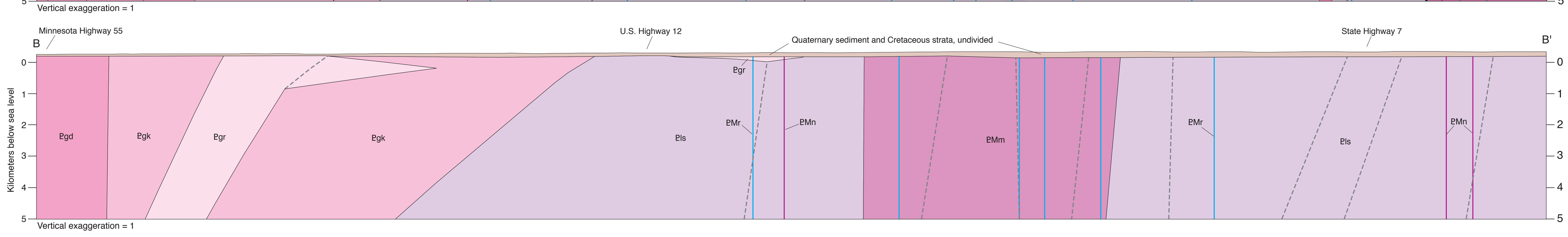
CORRELATION OF MAP UNITS

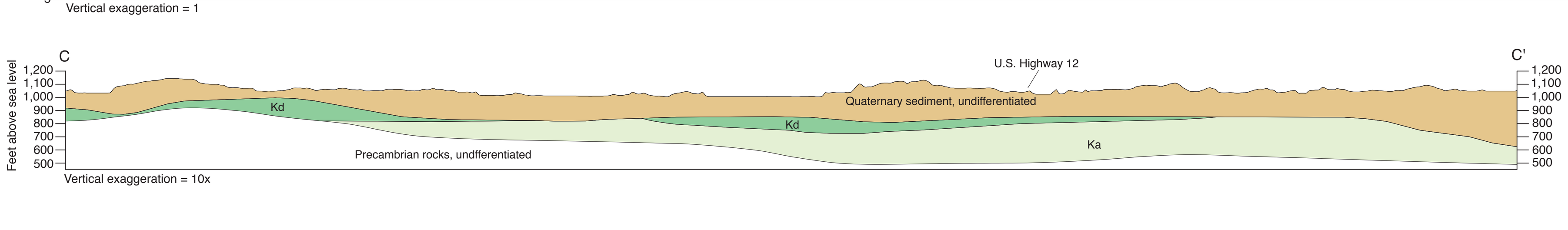
- Kd — Late Cretaceous; Ka — Early to Late Cretaceous? — MESOZOIC — PHANEROZOIC
- ƁMr, ƁMn, ƁMm — MESOPROTEROZOIC or PALEOPROTEROZOIC — PROTEROZOIC — PRECAMBRIAN
- Ɓmi, Ɓgu, Ɓgr, Ɓgk, Ɓgd, Ɓgp, Ɓls, Ɓmv — PALEOPROTEROZOIC — PROTEROZOIC — PRECAMBRIAN
- Agn, Agl — NEOARCHEAN — ARCHEAN — PRECAMBRIAN
- Amg — NEOARCHEAN to PALEOARCHEAN — ARCHEAN — PRECAMBRIAN

MAP SYMBOLS

- **Geologic contact**—Approximately located.
- **Fault**—Based primarily on aeromagnetic signatures.
- **Form line**—Inferred from aeromagnetic signatures reflecting structural fabric within Precambrian rocks, such as bedding, cleavage, layering, and magmatic foliation.
- A——A' **Location of geologic cross section.**







INTRODUCTION

The geologic map and cross sections on this plate depict the type, distribution, and structure of bedrock units lying beneath as much as 700 feet (213 meters) of unconsolidated Quaternary sediments in Meeker County. The map shows how the bedrock surface would appear if it were viewed from an aerial perspective and the overlying Quaternary sediments were stripped away. The uppermost bedrock units in Meeker County consist of a complex assemblage of Mesozoic (Cretaceous, 145 to 66 Ma), Mesoproterozoic (1,600 to 1,000 Ma), Paleoproterozoic (2,500 to 1,600 Ma), and Neoarchean (2,800 to 2,500 Ma) to Paleoarchean (3,600 to 3,200 Ma) rocks. Characteristics of each rock formation 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. Sections A–A' and B–B' emphasize relatively deep-seated Precambrian (Archean and Proterozoic) geology and have no vertical exaggeration. Consequently, the Mesozoic (Cretaceous) rocks on the map along these two sections are too thin to effectively portray at this vertical scale, and they are undifferentiated from the surficial materials. In contrast, section C–C' emphasizes the Cretaceous sequence, using a vertical exaggeration of 10x. The exaggeration needed to show the thin rock units gives the appearance of steeper slopes on the land surface and bedrock topography, and contacts that dip more steeply than true.

Due to the thick cover of Quaternary sediments, no bedrock outcrops exist in Meeker County, and relatively few drill holes reach bedrock, especially in the western half of the county. Wherever possible the map and cross sections were generalized using water-well and scientific drilling records (including holes drilled for this project), and previous geologic maps of adjacent areas (Chandler and Mossler 2009; Jirsa and others, 2011; Steenberg and Chandler, 2013). Most wells that reach bedrock in the county encounter either Mesozoic rocks or weathered bedrock known as saprolite, and very few penetrate to recognizable Archean or Proterozoic rocks. Consequently, mapping of Archean and Proterozoic geology relies extensively on aeromagnetic (airborne magnetic) and gravity data. The Archean and Proterozoic rocks of the region are known to be associated with pronounced variations in magnetization and density, which produces distinct anomalies in the aeromagnetic and gravity data (Chandler and others, 2008). These data, in combination with the existing drill hole control, were used to distinguish the Archean and Proterozoic bedrock units.

The aeromagnetic and gravity data used in Meeker County were acquired by statewide programs (Chandler, 1991; Chandler and Schaap, 1991). To improve the gravity coverage for geologic mapping, 55 new gravity stations were acquired in Meeker County as a part of this project. The aeromagnetic and gravity data were gridded at intervals of 328 and 3,281 feet (100 and 1,000 meters), respectively (Chandler, 2007; Minnesota Geological Survey file data), and enhanced for geologic mapping by computing the first and second vertical derivatives. Such a procedure enhances the aeromagnetic and gravity signatures of sources either at or near the bedrock surface. The utility of derivative-enhanced gravity and aeromagnetic data for mapping Precambrian geology is illustrated in Figure 1, which shows interpreted unit 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).

The subsurface structure of the Archean and Proterozoic rocks is based principally on two-dimensional (strike-infinite) modeling of gravity and magnetic data along profiles, with constraints provided by rock property data from samples collected in adjacent areas (Chandler and Lively, 2011). Where appropriate, end corrections have been applied to anomaly sources that terminate near the model profiles. The models along two selected profiles were altered until observed and anomaly signatures suitably matched, and these results were used to compose cross sections A–A' and B–B'. Lines designating faults and contacts on the cross sections are the same as used on the geologic map. The inferred structural grain of subsurface geology is indicated by gray dashed lines, which represent boundaries between contrasting bodies from the modeling. Modeling along these two sections indicate that the contacts of the large, intermediate-to-mafic plutons (units Ɓgd and ƁMm) typically dip steeply to near-vertical, in contrast with moderately to steeply north-dipping contacts of some granitic rocks (units Ɓgk and Ɓgr) with metamorphic rocks (unit Ɓls). Near the north end of profile B–B', a north-dipping body of granite (unit Ɓgr) is interpreted to have a shallow, sill-like extension to the south, on the basis of gravity and magnetic modeling. Modeling indicates that most gravity and magnetic signatures can be accounted for by sources within the upper 3 miles (5 kilometers) of the crust, although the contact between granitic rocks (unit Ɓgk) and metamorphic rocks (unit Ɓls) may extend as deep as 6 miles (10 kilometers; not shown on the cross sections).

The Archean and Paleoproterozoic rocks beneath Meeker County have been imprinted extensively by Proterozoic tectonism (see Fig. 2 for a full depiction of these rocks beneath the younger Mesozoic deposits). The Paleoproterozoic rocks are associated with the Penokean (~1,850 Ma) and Yavapai (~1,780 Ma) orogenies. These two plate-convergent events were associated with extensive accretion and magmatism, through which a considerable amount of crustal material was added to the southeastern margin of an Archean craton represented by the ~3,500 to 2,700 Ma Superior Province (Holm and others, 2007). During the Penokean orogeny, northwest-verging thrusting of Archean and Paleoproterozoic rocks formed a series of terranes in which disparate slivers of rock were tectonically stacked and metamorphosed (Southwick and Morey, 1991; Schulz and Cannon, 2007). Within this framework, the Archean rocks that are inferred to occur in northeastern Meeker County would most likely represent rocks of the Superior Province craton. The Yavapai orogeny in east-central Minnesota was contemporaneous with extensive emplacement of granitoid intrusions, which are collectively referred to as the East-Central Minnesota batholith (Holm and others, 2005), and the Paleoproterozoic intrusions interpreted in the northern and central parts of Meeker County are most likely related to this event. The latest magmatic event interpreted to have occurred in Meeker County is represented by northwest- to west-striking dikes (units ƁMr and ƁMn) of either Paleoproterozoic or Mesoproterozoic age.

The interpreted bedrock structures in Meeker County consist of faults that have been inferred from aeromagnetic signatures. A minor fault is inferred to cut east–northeastwards across the Paleoproterozoic rocks in the northern part of the county, and on the basis of anomaly offsets, it appears to be associated with a left-lateral offset of 984 to 3,281 feet (300 to 1,000 meters). A northeast-striking fault is also inferred near the northwestern margin of the county, and may be part of a much more extensive thrust fault system to the southwest (Jirsa and others, 2011). A generally northwest-directed convergence has been deduced for Paleoproterozoic tectonism in this part of North America (Holm and others, 2007), so the faults inferred in Meeker County could have originated as thrust or strike-slip faults.

A mantle of saprolite covers the Precambrian bedrock surface in most of Meeker County. Saprolite is a residuum of extensive chemical weathering that converted some or nearly all of the minerals in the hard crystalline bedrock into various clay minerals. Chemical weathering is carried out by fluids generated at the land surface moving into the bedrock, typically along fractures. The uppermost parts of saprolite horizons are typically the most weathered, and original igneous and metamorphic fabrics are not discernible. This generally grades downward into less altered crystalline material, then into hard, crystalline, Precambrian bedrock. Based on limited drill hole data, saprolite varies in thickness from a few feet to hundreds of feet. 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 removed by erosion; and 3. Saprolite is difficult to distinguish in most drilling records from glacial sediments and Cretaceous strata. The timing of weathering that produced saprolite is unknown; however, this type of alteration typically requires prolonged tropical climatic conditions, which were common in the Cretaceous period (~145 to 65 Ma), but also occurred during other time periods. Saprolite is present beneath Cretaceous strata and the Middle Cambrian Mt. Simon Sandstone (in subcrop east of Meeker County). Therefore, we know that saprolite development occurred on the same Precambrian surface at least twice, once prior to the deposition of the Middle Cambrian Mt. Simon Sandstone and likely again prior to the deposition of the Cretaceous sedimentary rocks.

The Cretaceous sedimentary rocks (units Kd and Ka), which locally cover Precambrian rocks in Meeker County, consist of poorly lithified mudstone and sandstone. The elevation of the surface on which the Cretaceous sediments were deposited is shown in Figure 3. The distribution of these rocks is inferred from the construction records of about 140 wells. The discontinuous, patchy distribution of Cretaceous rock represents remnants of a broader regional distribution that was incised and segmented by episodes of widespread erosion. 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 and geophysical techniques are typically inadequate to consistently distinguish these strata from quartz-rich Quaternary sand, organic-rich Quaternary lake sediments, or saprolite on top of Precambrian rocks. The Upper Cretaceous sedimentary rocks (unit Kd) are interpreted to represent the easternmost extension 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 the western interior of North America during the Late Cretaceous Period. This unit is lithologically similar to mudstones, siltstones, and sandstones from Nicollet and Brown Counties to the south that contain a rich and diverse assemblage of palynomorphs with pollen taxa that are considered to be no older than Late Cretaceous (late Cenomanian) in age (Hu and others, 2008). The Lower Cretaceous unit (Ka) was formally known and mapped as the Phanerozoic undifferentiated unit (ƁMu) in adjacent counties (Chandler and Mossler, 2009; Mossler and Chandler, 2009). Despite extensive pollen analysis from drill core in the region, this unit appears to be barren of datable pollen grains. A tentative age of latest Albian to Cenomanian is inferred from a single grain of gymnospermous pollen and a dinoflagellate cyst from lithologically similar strata in McLeod County to the southeast (Ravn, unpub. data, 2009).

The majority of water wells in Meeker County receive adequate groundwater from within the Quaternary sediments. Because of this, there is not a great need to drill into deeper water-bearing bedrock units. Less than 5 percent of wells in Meeker County receive groundwater from bedrock units. The majority (three-quarters) of these wells receive groundwater from within the Cretaceous sediments and only a quarter of them receive groundwater from Precambrian bedrock units. Due to their depth, little is known about the hydrostratigraphic properties of the bedrock units in Meeker County. However, based on rock lithology, some hydrostratigraphic properties can be inferred. Within the Cretaceous units the Dakota Formation is known to have thick beds of relatively permeable quartzose sandstone, and wells that are finished in the Dakota Formation in Meeker County yield significant water for domestic wells; therefore, it is considered an aquifer. Though a small number of wells receive water from the unnamed unit (Ka), it is composed of finer-grained quartzose sandstone and thicker silt and clay beds of low permeability in a vertical direction compared to the Dakota Formation and is therefore considered a confining unit. Groundwater flow in the few wells that receive water from the hard crystalline Precambrian bedrock is derived largely from water-bearing fractures in the Precambrian bedrock units, and the location of these permeable fracture zones is difficult to predict.

DESCRIPTION OF MAP UNITS

MESOZOIC

Kd **Dakota Formation (Upper Cretaceous)**—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 dark brown, non-calcareous, with light brown to white silty laminations. Black lignitic plant fragments, pisoid concretionary grains, and well-cemented siderite concretions have been found in drill cuttings and core. The formation is as thick as 150 feet (45 meters). It unconformably overlies the undifferentiated unit (Ka), saprolite, and Precambrian crystalline rocks in the county at elevations between 750 and 950 feet (244 to 289 meters) above sea level.

Ka **Undifferentiated rock (Lower to Upper Cretaceous?)**—Red-brown to pale olive-green mudstone, siltstone, and interbedded yellow-gray, very fine- to medium-grained sandstone containing small flakes of black lignite. Generally friable, but does contain local iron-rich concretions and intergranular carbonate and pyrite cement. Faint horizontal laminations and centimeter-scale beds are present in some intervals, other intervals are very uniform and massive, and some are convoluted by soft sediment deformation. The unit is as thick as 250 feet (76 meters) in southeast Meeker County. It unconformably overlies saprolite and Precambrian crystalline rocks in the county at elevations of 500 to 850 feet (152 to 259 meters) above sea level. The thickest sections appear to be preserved in topographic lows that were present on the Precambrian surface prior to deposition of the unit. Extensive pollen analysis from drill core in the region has revealed that the unit is barren of datable pollen grains, except for a single grain of gymnospermous pollen and a dinoflagellate cyst from lithologically similar strata in McLeod County to the southeast, from which a late Albian to Cenomanian age is tentatively inferred (Ravn, unpub. data, 2009).

MESOPROTEROZOIC or PALEOPROTEROZOIC

Diabasic to lamprophyric dike—Trajectories are wholly inferred from aeromagnetic signatures; based on exposures of similarly-striking dikes elsewhere, thicknesses may range from several feet to more than 328 feet (100 meters). They are subdivided here on the basis of magnetic polarity as inferred from signatures on aeromagnetic maps. The two polarity directions most likely reflect emplacement of the dikes at different times during fluctuations in pole positions.

ƁMr ***Reversely polarized dike***

ƁMn ***Normally polarized dike***

ƁMm **Mafic intrusion (gabbro, diabase) of unknown age—**Large plutons inferred from strongly positive gravity and magnetic anomalies and limited drill core data (Fig. 2; hole numbers BKV-81-1, LL-81-1, and NB-81-1). Generally medium- to coarse-grained, locally biotitic and pyroxenitic, may be locally cut by granitic dikes, and may locally have inclusions of co-magmatic and possibly supracrustal rocks.

PALEOPROTEROZOIC

Ɓmi **Mafic intrusion including pyroxenite, peridotite, gabbro, and lamprophyre—**Small dikes and plugs inferred from magnetic signature. A similar intrusion in Morrison County to the north is ~1,791 Ma (Keats and others, 2003), and others cut (and are therefore younger than) the Foley Granite (~1,774 Ma; Holm and others, 2005) in Benton County to the northeast.

Ɓgu **Granitic rock, undifferentiated—**Inferred from pronounced gravity lows.

Ɓgr **Granite—**Reddish, variably porphyritic, and massive; characterized by a variable magnetic signature and minor gravity lows. Its delineation is based on gravity and aeromagnetic signatures and regional geologic context (Jirsa and others, 2011). May be related to the St. Cloud Red (~1,779 Ma), Foley (~1,774, 1,779 Ma), Pierz (~1,779 Ma), and Richmond (~1,772 Ma) granites. All dates are from Holm and others (2005).

Ɓgp **Gabbro, pyroxenite, diorite, and lamprophyre (shown only on Figure 2)—**Lithologically similar to unit Ɓmi, but is variably magnetic and tends to occur in larger plutons. The unit occurs only in the northwest corner of the county. May include the approximately 1,780 Ma Watab quartz diorite (Holm and others, 2005) and the St. Wendell quartz gabbro in Stearns County to the north (Boerboom and others, 1995).

Ɓgk **Rockville Granite and rocks inferred to be related—**Weakly magnetic, coarse-grained granite, similar to a ~1,780 Ma granite exposed near Rockville to the north (Holm and others, 2005). Identification based on one drill core (Fig. 2; hole number BPL-88-12) and mapped on the basis of regional geologic context and on pronounced gravity lows.

Ɓgd **Gray granodiorite to granite intrusion—**Strongly magnetic granitic rocks with low to moderate densities. May be related to the Freedhem (~1,775, 1,776 Ma), Isle (~1,779 Ma), and Warman (~1,787 Ma) intrusions (Holm and others, 2005).

Ɓls **Little Falls Formation and rocks inferred to be related—**Schist and slate of graywacke-mudstone protolith, may locally include abundant dikes and sills of the above-described granitic rocks. Based primarily on areas with similar gravity (positive) and magnetic (subdued) signatures 31 to 62 miles (50 to 100 kilometers) to the north–northeast, known to be underlain by the Little Falls Formation (Chandler and others, 2008). Recent geochronologic analysis from drill core of the Little Falls Formation in Morrison County to the north indicates detrital zircons are as young as 1,844 Ma (Boerboom and others, 2014).

Ɓmv **Interlayered volcanic, volcaniclastic, sedimentary, and hypabyssal intrusive rock (shown only on Figure 2)—**Inferred to be a southern extension of rocks that were defined in east-central Minnesota on the basis of gravity and magnetic data, as well as limited drill core data (Chandler and others, 2008).

NEOARCHEAN

Agl **Leucogranite (shown only on cross section A–A')—**Occurs along the Yellow Medicine Shear Zone, a north-dipping structure that is interpreted to extend beneath unit Ɓls in the southern part of Meeker County. Structure is based on the southern extension of the gravity and magnetic model used to create cross-section A–A'.

Agn **Granitic to granodioritic orthogneiss—**Based on gravity and magnetic signatures and regional geologic context. Age dates from a drill core of rocks with similar geophysical attributes in Sherburne County to the northeast (Chandler and others, 2008) range from 3,180 to 2,800 Ma (Van Schmus and others, 2007). May also include equivalents of the 2,550 Ma McGrath Gneiss (Jirsa and others, 2011). Characterized by a moderately complex magnetic signature and a generally positive gravity signature.

NEOARCHEAN to PALEOARCHEAN

Amg **Granitic gneiss and migmatite—**Based on gravity and magnetic signatures and regional geologic context. Interpreted to be part of the Montevideo block of the approximately 3,500 to 2,600 Ma Minnesota River valley subprovince of the Superior Province.

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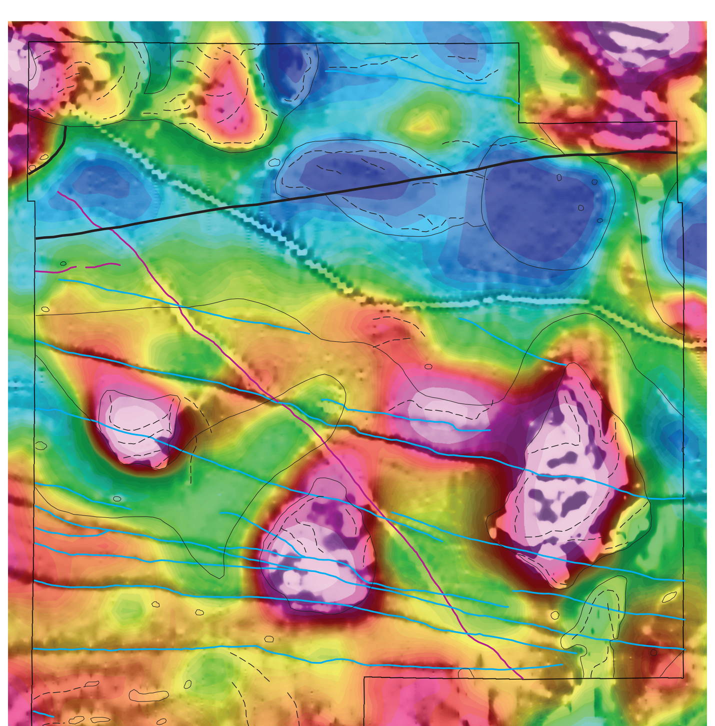

Figure 1. Superimposed geophysical images of first vertical derivative magnetic anomaly data (gray scale) and second vertical derivative gravity data (color) for the Meeker County area (scale 1:300,000). The range of first vertical derivative magnetic values is approximately -200 (black) to 200 (white) nanoTeslas/km, and the range of second vertical derivative gravity values is approximately -0.25 (blue) to 0.25 (magenta) milligals/km^2. The anomaly patterns reflect the geologic structure of the Precambrian bedrock that underlies the area, and therefore the Cretaceous units are not included on this figure (see Fig. 2 for the Precambrian geology map). Geologic contacts, faults, form lines, and dikes from the bedrock map are shown. The sharp, linear magnetic high extending east–west and southeast–northwest across the northern part of Meeker County is caused by a power transmission line.

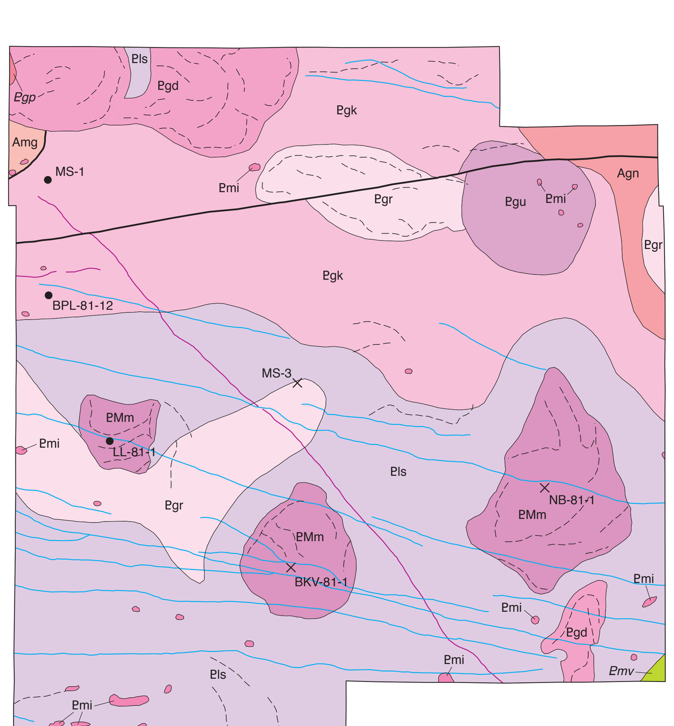

Figure 2. Map showing Precambrian bedrock geology at the sub-Cretaceous surface, scale 1:300,000. Contact lines, faults, and form lines from the bedrock map are shown. Dikes (units ƁMn and ƁMr) are also shown. The locations of core samples from drill holes that ended in Precambrian bedrock are shown as labeled points. These cores are available at the Minnesota Department of Natural Resources core storage facility in Hibbing, Minnesota.

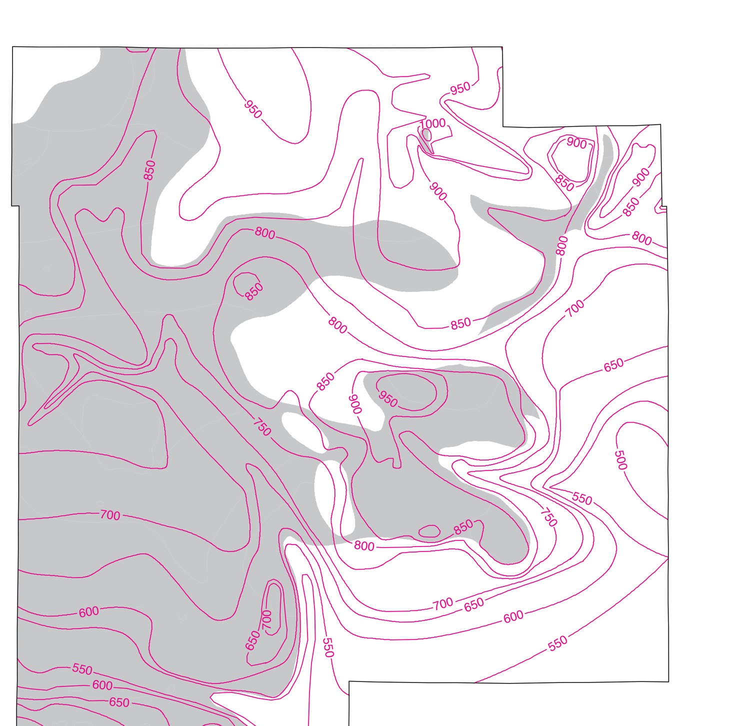

Figure 3. Elevation of the Precambrian bedrock surface; scale 1:300,000. Contour interval is 50 feet (15 meters). Contours are interpreted from water well records and seismic stations. White areas represent the surface on which the Cretaceous sediments were deposited. Shaded areas are where significant erosion has occurred, removing the Cretaceous sediments and partially eroding the Precambrian rocks at the surface.