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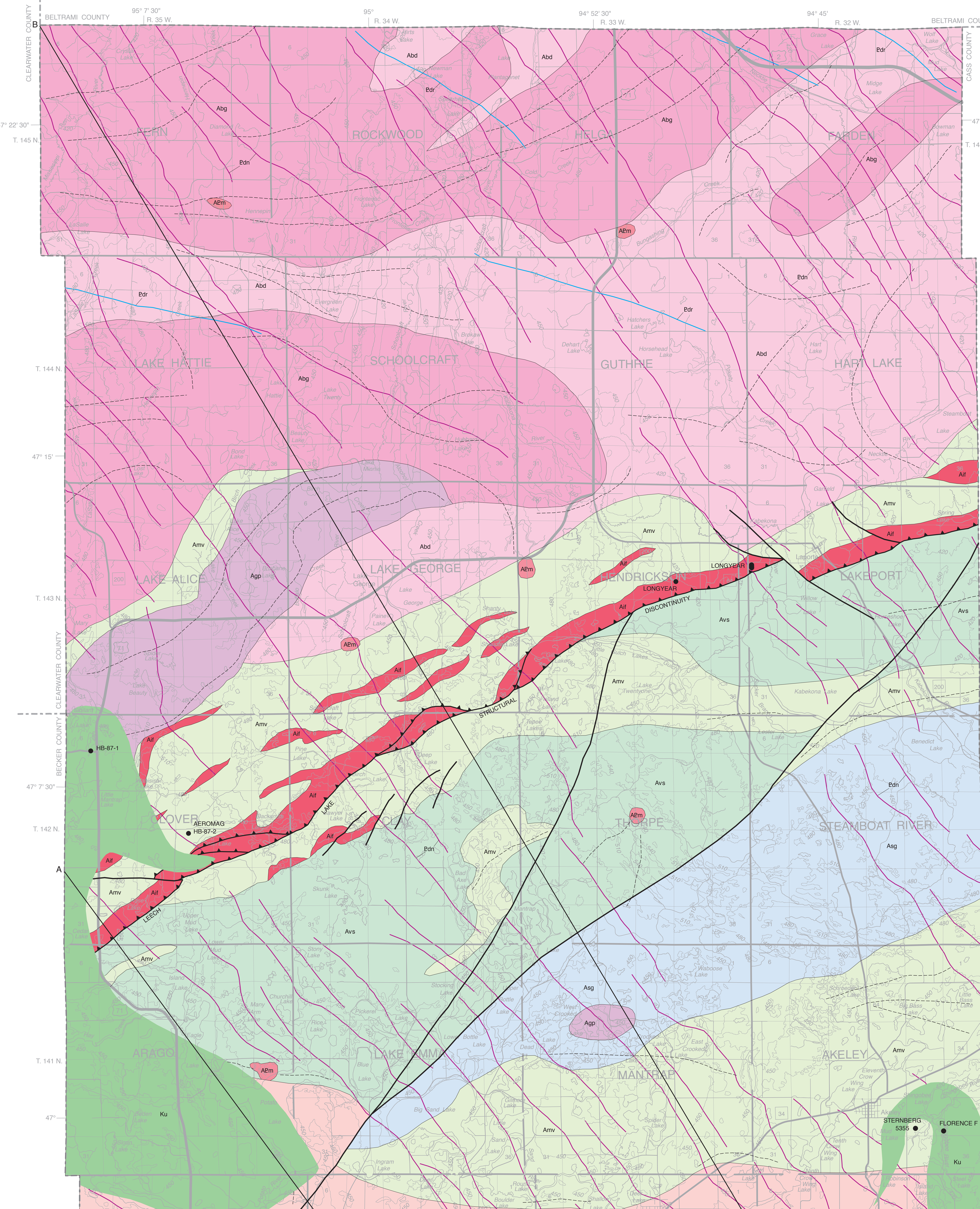
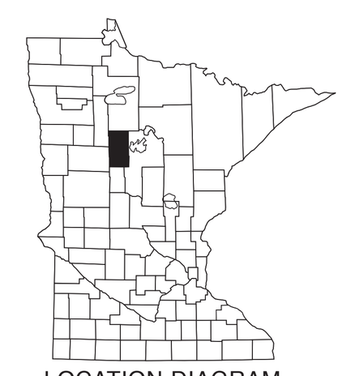


Digital base modified from the Minnesota Department of Transportation BaseMap data; digital base annotation by the Minnesota Geological Survey.
Elevation contours were derived from the U.S. Geological Survey 30-meter Digital Elevation Model (DEM) by the Minnesota Geological Survey.
Universal Transverse Mercator Projection, grid zone 15
1983 North American Datum

SCALE 1:100 000

CONTOUR INTERVAL 30 METERS

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



LOCATION DIAGRAM

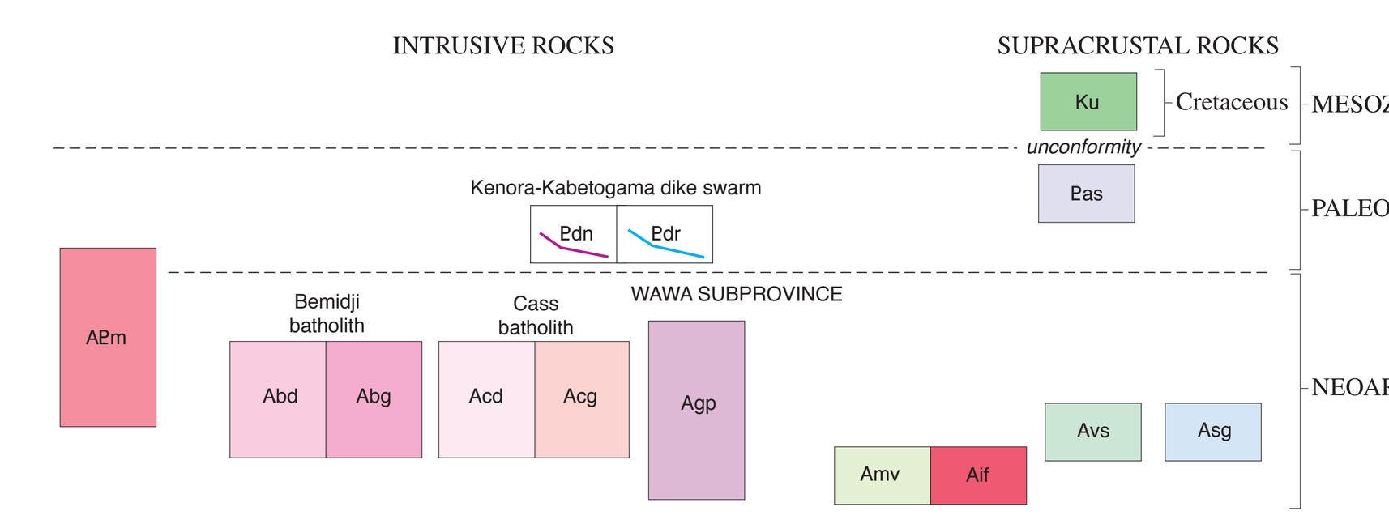
BEDROCK GEOLOGY

By

V.W. Chandler and Amy L. Radakovich

2018

CORRELATION OF MAP UNITS



MAP SYMBOLS

Geologic contact—Contacts in Archean and Proterozoic rocks are inferred exclusively from geophysical maps and models, locally anchored by drill-hole data. Geophysical modeling (Fig. 1) indicates that contacts between Precambrian units are steep to nearly vertical. The Cretaceous strata are shallowly dipping. Their positions are based on a limited drill-hole data set, and thus, no contact line is used. Dashed where concealed by rocks of the Animikie Group (unit Ᵽas).

Fault—Inferred from geophysical data; typically steeply dipping. Both strike-slip and dip-slip senses of fault motion are likely; however, the precise offset sense and amount is unknown.

Leech Lake Structural Discontinuity—Inferred from geophysical maps and models, and inferences based on our understanding of early tectonic processes to be a north-dipping thrust fault; teeth are on the upper (northern) block.

Foliation trajectory—A narrow, curvilinear aeromagnetic anomaly (contrasting high or low) inferred to mimic bedding or layering in supracrustal rocks, modal layering or magmatic flow in intrusive rocks, or metamorphic fabric (cleavage, schistosity, gneissic foliation). Trajectories depicted in some components of batholiths appear to delineate lobes of magma emplacement that may or may not be compositionally distinct.

Bedrock drill hole—Location of a drill hole that reached bedrock. Note that some of the drill holes labeled "Longyear" represent a series of several holes in close proximity; refer to Plate 1 of this atlas for more detail.

A —— A' **Line of geophysical modeling profile**—Shown on Figure 1.

INTRODUCTION

This geologic map and accompanying cross sections depict the bedrock formations lying beneath unconsolidated sediment of variable thickness (Plate 6, *Depth to Bedrock*) in Hubbard County. The bedrock consists chiefly of Precambrian metamorphic and intrusive crystalline rocks that are typically capped by a weathering residuum (saprolite), and are overlain locally by poorly consolidated Cretaceous sandstone and mudstone. Glacial till, outwash, river alluvium, and lake sediments deposited in the last 2 million years, and soils formed from them cover the bedrock across the entire county. These sediments vary in thickness from 150 feet (46 meters) to more than 1,000 feet (305 meters; Plate 6, *Bedrock Topography* and *Depth to Bedrock*). Most water wells in the county do not intersect bedrock because adequate water supplies are typically encountered within the overlying sediments. As a result, drill holes with useful information about the bedrock are scant and sparsely distributed (this plate and Plate 1, *Data-Base Map*). Well cuttings or drill cores were available from 11 of 17 drill holes that intersected bedrock in the county, and geologic information from these samples was incorporated in the bedrock mapping. Cuttings sets were processed and archived by the Minnesota Geological Survey, and core samples, which have been acquired as part of minerals exploration and other test drilling endeavors, are maintained by the Minnesota Department of Natural Resources in Hibbing. To augment this County Geologic Atlas mapping, several rotary-sonic holes were drilled primarily to sample the glacial deposits, and only one of these (drill hole HBR-3) intersected bedrock, consisting of a Cretaceous mudstone. Given the lack of bedrock outcrop and sparse drill-hole information in Hubbard County, the geology depicted here is largely inferred from geophysical data—specifically gravity and magnetic data (Fig. 1). The interpretation of geophysical data is guided by relationships observed in similar geologic terranes in northeastern Minnesota (Fig. 2), where bedrock is variably well exposed (Jirsa and Boerboom, 2003; Jirsa and Miller, 2004; Jirsa and Chandler, 2007), as well as in the more extensively drilled areas of northwestern Minnesota (Jirsa and others, 1999; Chandler and others, 2014). A detailed description of the gravity and magnetic data, and the interpretative procedures employed in creation of this map, are given below. The bedrock geology presented here represents a revision from that shown on the statewide map (Jirsa and others, 2011), and generally conforms with that from recent mapping in adjacent Wadena (Radakovich and Chandler, 2016), Becker (Jirsa and Chandler, 2016), and Cass (Radakovich and Chandler, 2018) Counties (Fig. 2).

GEOLOGIC SETTING

Hubbard County is underlain by Precambrian crystalline and sedimentary bedrock of Neoarchean (approximately 2,700 million years old, or Ma) and Paleoproterozoic (1,800 to 2,100 Ma) ages, and the eroded remnants of sedimentary rocks deposited by marine transgression during the Cretaceous time period (approximately 145 to 65 Ma). The Neoarchean rocks are part of the Wawa subprovince of the Superior Province (Fig. 2)—a complex, deformed, and metamorphosed assemblage of volcanic and sedimentary rocks that were cut by various intrusions. The Wawa assemblage was formed approximately 2,720 to 2,650 Ma with the accretion of oceanic and proto-continental materials onto the developing southern margin of what was to become the North American craton (Williams, 1990). The oldest known components in the subprovince are the metavolcanic and local metasedimentary rocks, referred to collectively as supracrustal rocks, or simply greenstones (units Amv, Avs, Aif, Asg). These rocks are inferred to be approximately 2,722 Ma in age, based on exposures of similar rocks in northeastern Minnesota (Peterson and others, 2001). These rocks were tightly folded and thrust faulted into near-vertical orientation, and metamorphosed predominantly to greenschist facies, although higher grades may exist locally, such as along contacts with large intrusions. The supracrustal rocks form remnant screens between several large complexes of granitic intrusions that are referred to here as the Bemidji and Cass batholiths (units Abg, Abd, Acg, Acd).

A variety of younger intrusions were emplaced into both the batholiths and surrounding supracrustal rocks during Neoarchean and Paleoproterozoic times. The relative timing of intrusions is inferred from cross-cutting relationships observed elsewhere in drill cores or outcrops, or from apparent cross-cutting relationships inferred from geophysical signatures. Discrete, positive magnetic anomalies that correspond to positive gravity signatures are inferred to represent Neoarchean mafic (gabbroic) plutons (unit Agp). Magmatic biotite from a geophysically similar intrusion northwest of Hubbard County yielded a Neoarchean age of 2,639 ± 7 Ma using Ar-Ar methods (Jirsa and others, 2006), and the interpreted intrusions in Hubbard County may be equivalent. A group of mafic to ultramafic plutons (unit AᵽM) that may be either Neoarchean or Paleoproterozoic in age is identified by small, positive magnetic anomalies—generally too small to be intersected by the network of widely spaced (approximately 1.61 kilometers) gravity data measurements. Drill cores from two such anomalies were recovered in nearby Clay County (Chandler and others, 2014) to the west. The Neoarchean bedrock of Hubbard County is cut by Paleoproterozoic diabasic dikes (units Ᵽdr, Ᵽdn). They represent the western part of the Kenora-Kabetogama dike swarm (Southwick and Day, 1983), which is dated at about 2,067 Ma (Buchan and others, 1996). The dikes are manifest geophysically as narrow, linear, northwest-striking magnetic anomalies. The anomalies have both positive and negative signatures (Fig. 1) that may reflect variations in the direction of the earth's magnetic field at the time of dike emplacement, or during subsequent alteration. Based on exposures to the east, the dikes in Hubbard County may range in width from a few feet (1 meter) to as much as 300 feet (91 meters).

Between 1.9 and 1.7 Ga, a series of collisional, mountain-building events associated with the Penokean and Yavapai Orogenies occurred along the southern edge of the Archean Superior Province to the southeast of Hubbard County (Fig. 2). The loading of new materials along the edge of the Superior Province caused the crust to the north of the mountain fronts to down-warp into a foreland basin, which was filled by sedimentary rocks of the Paleoproterozoic Animikie Group. The main bowl of the Animikie basin lies to the east of Hubbard County (Fig. 2), where it contains a shallowly-dipping, generally undeformed sedimentary sequence, in which basal quartzite and iron-formation are overlain by a thick argillite to graywacke sequence. The Nimrod outlier (Fig. 2), which is understood to be an erosional remnant of the larger Animikie basin, extends into southern Hubbard County. Only the upper argillite sequence (unit Ᵽas) has been identified in the Nimrod outlier, possibly consistent with its location at a more distal part of the original Animikie Basin.

Faulting of various kinds has likely occurred at several times during the evolution of this area. The most prominent feature on the bedrock map is a major east–northeast-trending structure visible on geophysical images (Fig. 1) and known as the Leech Lake Structural Discontinuity. It is inferred to be a series of anastomosing faults that may represent a fundamental terrane boundary formed in Archean time during accretionary assembly of the Superior craton (Jirsa and others, 1992). Though dissected by subsequent faulting, the Leech Lake Structural Discontinuity can be traced across nearly the entire state (Fig. 2). In areas to the northeast of Hubbard County, where the geology is better constrained by outcrop and drilling, it is interpreted to be a relict zone of thrust faulting. It is shown here with teeth on the inferred upper (northern) plate, which is consistent with that interpretation and with the northward dip direction indicated by geophysical modeling (Fig. 1). Although The Leech Lake Structural Discontinuity is primarily an Archean structure, it is likely to have undergone reactivated movements many times, some possibly even during recorded history. Twenty minor to moderate earthquakes have been recorded in Minnesota since the 1860s (Chandler, 2014), and four have occurred either near or along the Leech Lake Structural Discontinuity, including two to the immediate west in Becker County (in Detroit Lakes and Evergreen; Jirsa and Chandler, 2016) and one to the east in Cass County (in Walker).

A mantle of saprolite covers most of the Precambrian rock surface beneath Hubbard County. Saprolite is a residuum of extensive chemical weathering in which some or nearly all of the minerals in the bedrock were converted to various clays. Typically the uppermost parts of saprolite horizons are the most weathered, and original igneous or metamorphic fabrics are not discernible. The severity of weathering progressively decreases with depth, and original fabrics are locally preserved despite partial replacement of feldspar and other minerals by clays. Based on scant drill-hole data, saprolite in Hubbard County ranges from a few feet (1 meter) to as much as 72 feet (22 meters) thick. Studies elsewhere in Minnesota (Setterholm and Morey, 1995) indicated that saprolite can be considerably thicker, especially along weathered vertical fractures. Saprolite cannot be mapped in a meaningful way given the current distribution of data, but it is likely to be present beneath glacial sediments in most of the county. The timing of weathering processes that formed saprolite is unknown; however, this type of alteration typically requires tropical climates, which were common in the Cretaceous (approximately 145 to 65 Ma) and other time periods. Isolated and thin patches of Cretaceous sedimentary strata locally overlie saprolite, implying that weathering occurred before or during deposition of those strata.

The presence of Cretaceous strata (unit Ku) is inferred from the construction records of five wells and drill core in the county and one scientific drill hole just inside the Becker County border to the west (drill hole HB-87-3). The strata were intersected in drill holes in the western, southwestern, and southeastern parts of the county, and are likely present elsewhere in the county. The Cretaceous strata typically consist of dark gray to black shale to silty clay to rare white sandstone. Intersected thicknesses vary from 4 to 62 feet (1 to 19 meters) within Hubbard County, although not all holes were drilled completely through the Cretaceous strata into the Precambrian rocks below. Drill hole HB-87-3 in Becker County was the keystone hole used to interpret the stratigraphy of this unit. This hole encountered a 312-foot (95-meter) Cretaceous sequence consisting of predominantly dark gray shale with increasing siltstone and sandstone interlayers and rare lignite with depth (Southwick, 1990). These strata are interpreted to be of Cenomanian to Turonian in age and to represent all or parts of the Carlile Shale, Greenhorn Formation, Graneros Shale, and possibly the Dakota Formation that is exposed in southwestern Minnesota and South Dakota (Setterholm, 1994). It is common for the basal Cretaceous strata to have a significant content of material derived from the underlying saprolite, and the overlying Quaternary sediments commonly contain fragments of eroded Cretaceous strata. This obfuscates the differentiation from well records of these three units (saprolite, Cretaceous strata, and Quaternary sediments). Cretaceous strata are essentially transparent to the geophysical techniques employed here and thus, their depiction is based on only those few drill-hole records that are sufficiently detailed to differentiate. As a result, the depiction of the Cretaceous strata that are shown here probably under-represents their true extent, and so no boundaries are presented along the edges of these mapped units. Unit shapes, however, have been modified at the authors' discretion to support the supposition that Cretaceous units remain along Precambrian bedrock valley walls where they have not been eroded (Plate 6).

GEOLOGIC CROSS-SECTIONS

Computer modeling of gravity and magnetic anomaly data was conducted along two profiles in the county (Fig. 1, cross sections A–A' and B–B') to provide some insight into the third dimension—particularly relevant to interpretations of Precambrian bedrock. The geophysical models of these profiles were modified slightly in Figure 1 to depict a more schematic interpretation based on what is known about the bedrock, and to highlight important features. *All models and the data on which they are based appear in digital files that accompany this geologic atlas.* Constrained in part by rock properties data (specific gravity and magnetic susceptibility measurements) derived from similar rock types elsewhere in Minnesota (Chandler and Lively, 2011a), the modeling indicated that observed anomaly signatures could be accommodated by geologically reasonable sources extending down to depths of approximately 4.3 miles (7 kilometers). A 4.3-mile (7-kilometer) depth extent was also supported by magnetic model studies investigating the roots of a strongly magnetic iron-formation in adjacent Becker County (Jirsa and Chandler, 2016) to the west.

The approximately 4.3-mile (7-kilometer) depth extent interpreted here for the Archean supracrustal rocks is surprisingly shallow, given the vertical geometry and the relatively greater width of the greenstone belt that they collectively form. This near-vertical but shallow-rooted geometry is a common trait of greenstone belts worldwide, which typically have depth extents less than 6.2 miles (10 kilometers), even though their widths in map-view can be tens of kilometers (Dentith and others, 1992; Wellman, 2000; Peschler and others, 2004). Most greenstone belts are therefore thought to be truncated at shallow crustal depths, either tectonically by low-dipping faults or magmatically by intrusions (Jackson and others, 1990; Ludden and others, 1993; Goleby and others, 2004). Geophysical studies elsewhere in the Superior Province indicated that greenstone belts are underlain either by granitic rocks or mixed granitic and metasedimentary rocks (Young and others, 1986; Ludden and others, 1993). Below 4.3 miles (7.0 kilometers) deep in our models, a magnetic rock of intermediate composition, such as a granodiorite (gray unit on Fig. 1 cross sections) is assumed, which is consistent with gravity and magnetic model studies of crustal structure in central Minnesota (Chandler and others, 2007, 2008).

Profile A–A' (Fig. 1) defines a northwest–southeast section that crosses the Leech Lake Structural Discontinuity and the northern part of the Nimrod outlier. This model indicates that structures associated with the Leech Lake Structural Discontinuity dip vertically to steeply (80°) northward. Other sources within the Archean rocks to the south indicate dips that range from near-vertical to about 60° northward. A feather-edge is interpreted for the Animikie sequence along the northern rim of the Nimrod outlier, but inwards these strata are interpreted to thicken abruptly to form a 0.9- to 1.1-mile (1.5- to 1.75-kilometer) thick section in south-central Hubbard County (Fig. 1). Profile B–B' (Fig. 1) defines a northwest–southeast section that crosses the southern margin of the Bemidji batholith, the Leech Lake Structural Discontinuity, a broad belt of greenstones, and the northern margin of the Cass batholith. Contacts within the Bemidji batholith are interpreted to dip steeply northward (approximately 80°) to vertical, as do the southern contacts of the batholith and adjacent contacts associated with gabbroic and metavolcanic rocks. Contacts and faults that are associated with the Leech Lake Structural Discontinuity are interpreted to dip about 75° northward. Contacts associated with the Archean greenstone rocks in the central part of Hubbard County are interpreted to dip vertically to steeply (80°) northwards, as do the contacts and internal features associated with the Cass batholith to the south (Fig. 1).

POTENTIAL FOR MINERAL DEPOSITS IN BEDROCK

A valid potential exists for economic mineral deposits in bedrock beneath Hubbard County, because rocks of the Superior Province are known to host a wide variety of base and precious metal mineral occurrences. These include komatiitic nickel deposits, iron-formation, volcanogenic massive sulfide (VMS) deposits, lode gold, and granitoid-associated deposits, as well as nickel-copper, platinum group element, chromium, and titanium deposits associated with mafic to ultramafic intrusions (Poulsen and others, 1992; Jirsa and others, 2006). Some potential may also exist for the presence of rock types that host diamonds (Thorleifson and others, 2007). All of this mineral potential, however, is unproven in Hubbard County. The thick glacial deposits that overlie bedrock in the county make test drilling expensive, and tend to thwart some of the geophysical methods typically used in mineral exploration. Thus, relatively little mineral exploration has been done in the region, with the following exception. In 1910, the E.J. Longyear Company drilled a series of six holes in the Kabekona Lake area in northeastern Hubbard County (this plate and Plate 1). These drill holes, consisting of a single hole in T. 143 N., R. 33 W., sec. 14, and five along a north–south profile in T. 143 N., R. 32 W., sec. 18, were located on the basis of magnetic dip-needle surveying, and were targeted on the iron-formation bearing metavolcanic units (unit Aif) along the Leech Lake Structural Discontinuity. Based on the driller's descriptions and our observations of cutting samples on file at the Minnesota Geological Survey, this drilling encountered weathered iron-formation, phyllite, schist, and ferruginous slate at depths of 393 to 456 feet (120 to 139 meters) below the land surface. None of the drill samples apparently contained sufficient iron content to warrant the costs of mining at such depths. Although this conclusion may still be valid today, the potential exists for future exploration and extraction of iron and other minerals in the bedrock of Hubbard County, especially with improvements in geophysical and drilling techniques in such deeply covered areas.

DESCRIPTION OF AEROMAGNETIC AND GRAVITY DATA AND INTERPRETIVE PROCEDURES

Aeromagnetic data (airborne measurements of the earth's magnetic field) are sensitive to subsurface variations in the abundance and physical characteristics of magnetic minerals, consisting chiefly of magnetite, which is a common accessory mineral in igneous, metamorphic, and some sedimentary rocks. The aeromagnetic data used in this study were acquired by a statewide program of high-resolution surveying (Chandler, 1991). The data in Hubbard County were acquired along north–south lines that were flown 1,312 feet (400 meters) apart at a mean terrain clearance of 492 feet (150 meters). The line data have been corrected for temporal variations, as well as for the effect of the regional geomagnetic field (DGRF model, National Oceanic and Atmospheric Administration, 1995), and have been interpolated into gridded data. The gridded aeromagnetic data used in this study were from a statewide, 328-foot (100-meter) spaced grid that was produced as part of a program to upgrade the aeromagnetic data base in Minnesota through reprocessing (Chandler, 2007). This statewide grid represents the magnetic anomaly data as observed at a level of 492 feet (150 meters) above the land surface. The gridded data were reduced to vertical polarization (reduce to pole), which corrects for the inclination of the earth's magnetic field, thereby placing anomalies more directly above their sources. The use of the aeromagnetic data for bedrock mapping was improved by computing first and second vertical derivative grids, which enhances the signature of magnetic sources at or near the bedrock surface.

Gravity data, which here are based on measurements taken at the land surface, are sensitive to density variations within the bedrock, which in turn reflect variations in bulk composition. The gravity data used in this study were derived from a statewide data base (Chandler and Lively, 2011b), which in Hubbard County consists of stations spaced about 1 mile (1.6 kilometers) apart. The gravity data were corrected for latitude- and elevation-related effects using standard procedures (International Association of Geodesy, 1971), a sea-level datum, and a Bouguer reduction density of 2,670 kg/cc. The reduced data were subsequently used to produce a 0.5-mile (805-meter) spaced grid of the Bouguer gravity anomaly for Hubbard County and surrounding areas. Following upward continuing of the Bouguer grid 1.2 miles (2 kilometers) to mitigate noise, the data were enhanced by computing a second vertical derivative grid. Similar to derivation of the magnetic data, the second vertical derivative operation enhances the signature of sources at or near the bedrock surface, thereby improving the utility of the gravity data for geologic mapping.

Because of their greater degree of resolution, the first vertical derivative and second vertical derivative aeromagnetic data were used to infer the majority of geologic features in the Precambrian bedrock, including contacts, dikes, and faults. Contacts were inferred around zones of distinct and internally consistent magnetic signature, whereas faults were inferred along distinct, linear trends that commonly appeared to truncate magnetic signatures on either side. Dikes were inferred along narrow, linear anomalies that did not appear to truncate or offset background anomaly signatures. In areas lacking magnetic contrast, the second vertical derivative gravity data were used in some instances to map contacts and faults.

The relationships between anomaly signatures and mapped geologic units are shown on the map in Figure 1, which superimposes second vertical derivative gravity data (color scale), first vertical derivative magnetic data (gray scale), and interpreted geology (black and white lines). Low-density, non-magnetic units, such as metasedimentary rocks (unit Avs) and the granitic rocks of the Bemidji (unit Abg) and Cass (unit Acg) batholiths, are characterized by negative second vertical derivative gravity signatures (blue and green colors) and a subdued first vertical derivative magnetic signature (darker shades). Moderately dense and magnetic rocks, such as the intermediate units of the Bemidji (unit Abd) and Cass (unit Acd) batholiths are characterized by positive signatures in both the second vertical derivative gravity data (yellow and orange colors) and the first vertical derivative magnetic data (light shading). Dense and strongly magnetic rocks, such as mafic intrusions (unit Agp) and the iron-formation-bearing parts of metavolcanic rocks (unit Aif), are characterized by strongly positive second vertical derivative gravity (red colors) and first vertical derivative magnetic (light shades) signatures. Dense, non-magnetic metavolcanic rocks (unit Amv) are characterized by strongly positive second vertical derivative gravity signatures (red colors) and subdued first vertical derivative magnetic signatures (darker shades). Such relationships were used in conjunction with existing information from drill holes and comparisons with better-known terranes elsewhere in the state to produce the bedrock geologic map.

Owing to the ambiguities of gravity and magnetic interpretation, the geologic map presented here should be used with appropriate caution, and significant revisions may occur locally, should new drill-hole data become available. Note that the geophysical data do not portray variations in material content, thickness, or distribution of the relatively thin, flat-lying Quaternary sediments, Cretaceous strata, or saprolite.

DESCRIPTION OF MAP UNITS

MESOZOIC

Ku **Clay, shale, and rare sandstone**—Dark gray to black shale to silty clay with rare lignite, to rare white kaolinitic sandstone; poorly lithified. Occurrence is inferred from scant subsurface data from five drill holes in Hubbard County and one drill hole just over the border in Becker County. Intersections in Hubbard County vary from 4 to 62 feet (1 to 19 meters) of gray clay and shale to white kaolinitic sandstone. Two of these holes finish in Cretaceous strata without reaching the base of the sequence. The hole just inside Becker County interesects 312 feet (95 meters) of dark gray to black shale with siltstone to sandstone interbeds before reaching Precambrian bedrock. Unit is likely more extensive than mapped. See Geologic Setting section for further explanation.

PALEOPROTEROZOIC

Ᵽas **Sedimentary rocks of the Nimrod outlier**—Shale and graywacke thought to be related to similar rocks of the Animikie basin to the east (Jirsa and others, 2011).

Kenora-Kabetogama dike swarm—Diabasic dikes that cut across most of western and northern Minnesota (Fig. 2). Based on outcrops farther east, the dikes consist of medium- to coarse-grained diabase, diorite, and gabbro having very fine-grained margins. The diabasic to gabbroic rocks encountered in drill hole HB-87-1 (this plate and Plate 1) likely represents one of these dikes. In outcrop the dikes are typically vertically dipping and widths range from a few feet (1 meter) to as much as 300 feet (91 meters). Depiction here is inferred from narrow, linear magnetic anomalies. The anomalies are subdivided on the basis of magnetic expression that reflects inherent polarity differences. Recognition of dike anomalies relies to a great extent on the geophysical contrast between diabase and the host rocks in which they occur. This results locally in the probably unrealistic depiction of dikes as segmented or terminated along lithologic boundaries between host rocks. It is likely that dikes extend farther along their apparent strike than portrayed here. Note that clusters of closely spaced dikes locally produce positive gravity signatures (Fig. 1). Magnetic susceptibility is 0.012-0.025 SI.

Ᵽdn ***Dike having a net normal magnetic polarity***—Inferred from a linear, positive aeromagnetic anomaly signature. Dashed where concealed by sedimentary rocks of the Nimrod outlier

Ᵽdr ***Dike having a net reversed magnetic polarity***—Inferred from a linear, negative aeromagnetic anomaly signature. May in some cases represent fractures in the bedrock where magnetic oxides have been degraded by alteration or weathering.

PROTEROZOIC or NEOARCHEAN

AᵽM **Magnetic intrusion**—Discrete, semicircular, aeromagnetic anomalies that are typically less than 1 mile (1.6 kilometers) in diameter, typically too small to have been intersected by the gravity network. Despite this, a mafic to ultramafic composition is inferred, based on drill-hole and outcrop data observed elsewhere (Jirsa and others, 2006). Composition may be similar to unit Agp.

NEOARCHEAN

Intrusive rocks

Bemidji batholith—A complex array of mostly granitic intrusions based wholly on geophysical attributes because no drill core or cuttings are known to exist. On this basis, it appears to contain multiple lobes of varied, generally granitic composition.

Abg ***Granitic phase***—Inferred to consist chiefly of granitic to granodioritic rocks, based on a geophysical expression of low gravity and moderate aeromagnetic signatures. As observed elsewhere, the granitic phase may be more strongly magnetic against its contact with supracrustal and intrusive host rocks. May be similar to unit Acg of the Cass Batholith.

Abd ***Granodioritic to dioritic phase***—Inferred to consist chiefly of granodioritic to dioritic rocks, based on geophysical attributes of moderate to high magnetic and gravity expression. May also include tonalitic phases as well as supracrustal inclusions. The magnetic signatures between these anomalies and the surrounding granitic phase (unit Abg) are commonly diffuse, consistent with the interpretation of these bodies being intrusive phases of the batholith, rather than discrete intrusions into it. May be similar to unit Acd of the Cass batholith.

Cass batholith—An informal name applied here to a suite of generally granitic rocks in central Cass County that extends west through parts of Hubbard and Becker Counties. In eastern Hubbard County, the Cass batholith appears to be in fault contact with, though possibly equivalent to, parts of the Giants Range batholith (Jirsa and others, 2011).

Acg ***Granitic phase***—Inferred to consist chiefly of granitic to granodioritic rocks, based on a geophysical expression of low gravity and moderate aeromagnetic signatures. As observed elsewhere, the granitic phase may be more strongly magnetic against its contact with supracrustal and intrusive host rocks. May be equivalent to unit Abg of the Bemidji batholith.

Acd ***Granodioritic to dioritic phase***—Inferred to consist chiefly of granodioritic to dioritic rocks, based on geophysical attributes of moderate to high magnetic and gravity expression. May also include tonalitic phases as well as supracrustal inclusions. A biotite gneiss reported in drill hole OB-29034 is interpreted to represent such an inclusion. The magnetic signatures between these anomalies and the surrounding granitic phase (unit Acg) are commonly diffuse, consistent with the interpretation of these bodies being intrusive phases of the batholith, rather than discrete intrusions into it. May be equivalent to unit Abd of the Bemidji batholith.

Agp **Gabbro, peridotite, pyroxenite, diorite, lamprophyre, and metamorphic equivalents**—Locally defined by variably high gravity and magnetic signatures. Includes an irregular, belt-like body that lies north of the Leech Lake Structural Discontinuity in west-central Hubbard County and an ovoid body in the central part of the county. Magmatic biotite from a geophysically similar intrusion northwest of Hubbard County yielded a Neoarchean age of 2,639 ± 7 Ma using Ar-Ar methods (Jirsa and others, 2006). However, based on work elsewhere, some units so labeled may be more closely allied with metavolcanic sequences and therefore much older.

Supracrustal rocks

Asg **Volcanogenic metasedimentary rocks**—Inferred to consist chiefly of graywacke and mudstone similar to those of the Lake Vermilion Formation in northeastern Minnesota (Jirsa and Boerboom, 2003). Rocks are associated with a very subdued magnetic anomaly expression and intermediate to low gravity signatures.

Avs **Volcaniclastic rocks**—Inferred to be schistose volcaniclastic and epiclastic rocks of felsic to intermediate composition. In correlative terranes that are exposed further to the east (Jirsa and Boerboom, 2003), similar geophysical expression (low gravity and magnetic signatures) is associated with schist and other metasedimentary rocks of graywacke and volcanogenic graywacke protolith. May contain thin volcanic strata locally.

Aif **Iron-formation**—Narrow, curvilinear magnetic highs inferred to represent layers and lenses of lean, magnetite-bearing iron-formation interbedded with metavolcanic and other metasedimentary strata. Iron-formation consists of iron-rich mudstone (now slate) and chert, locally interbedded with graphitic, argillaceous, and volcanogenic strata. Some of the lower amplitude and diffuse-edged anomalies may be magnetite-bearing volcanic layers. In Hubbard County, this unit is interpreted to occur chiefly as lens-like masses within the metavolcanic rocks that lie along either side of the Leech Lake Structural Discontinuity. The only samples of this unit are from a series of test holes in the northeastern part of the county that were drilled by the E.J. Longyear Company in 1910. On the basis of driller's descriptions and cutting samples available on file at the Minnesota Geological Survey, this drilling encountered weathered iron-formation, phyllite, schist, and ferruginous slate. Magnetic susceptibility is 0.004-0.704 SI.

Amv **Mafic metavolcanic rocks**—Includes basalt, minor volcaniclastic and hypabyssal intrusive rocks; metamorphosed under lower greenschist to lower amphibolite facies conditions. Defined by high gravity signatures and by a generally subdued magnetic expression. May include some calc-alkalic rocks.

REFERENCES

Numbers in parentheses refer to published maps shown on Figure 2 and cited in the text.

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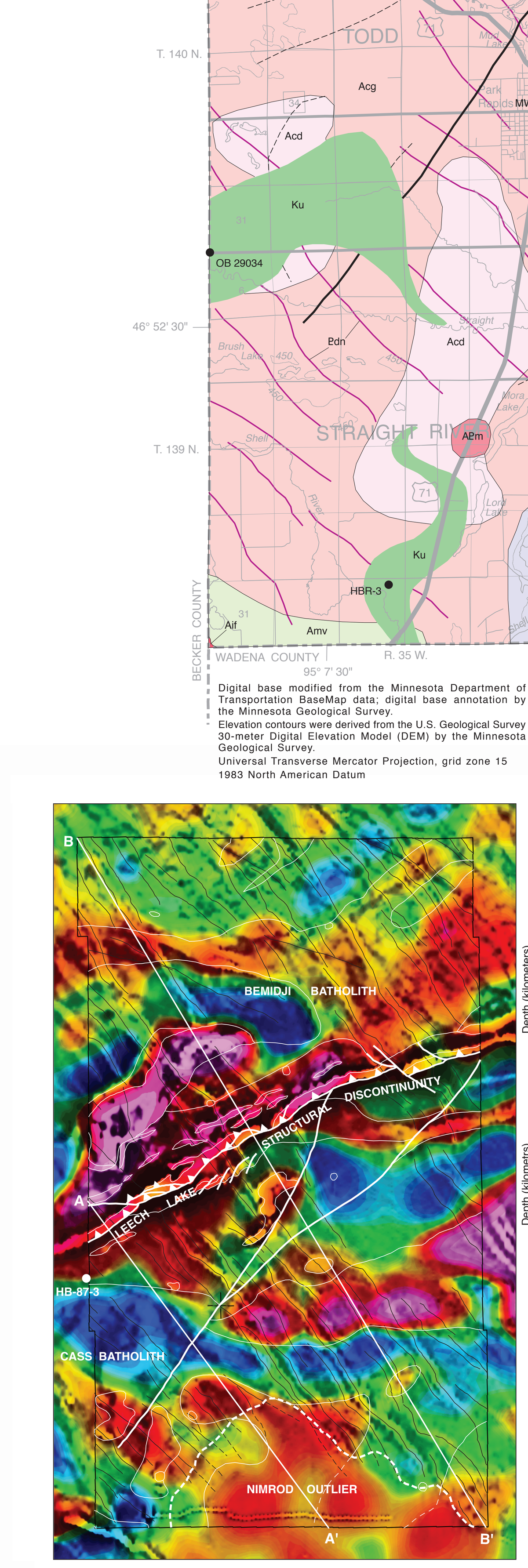

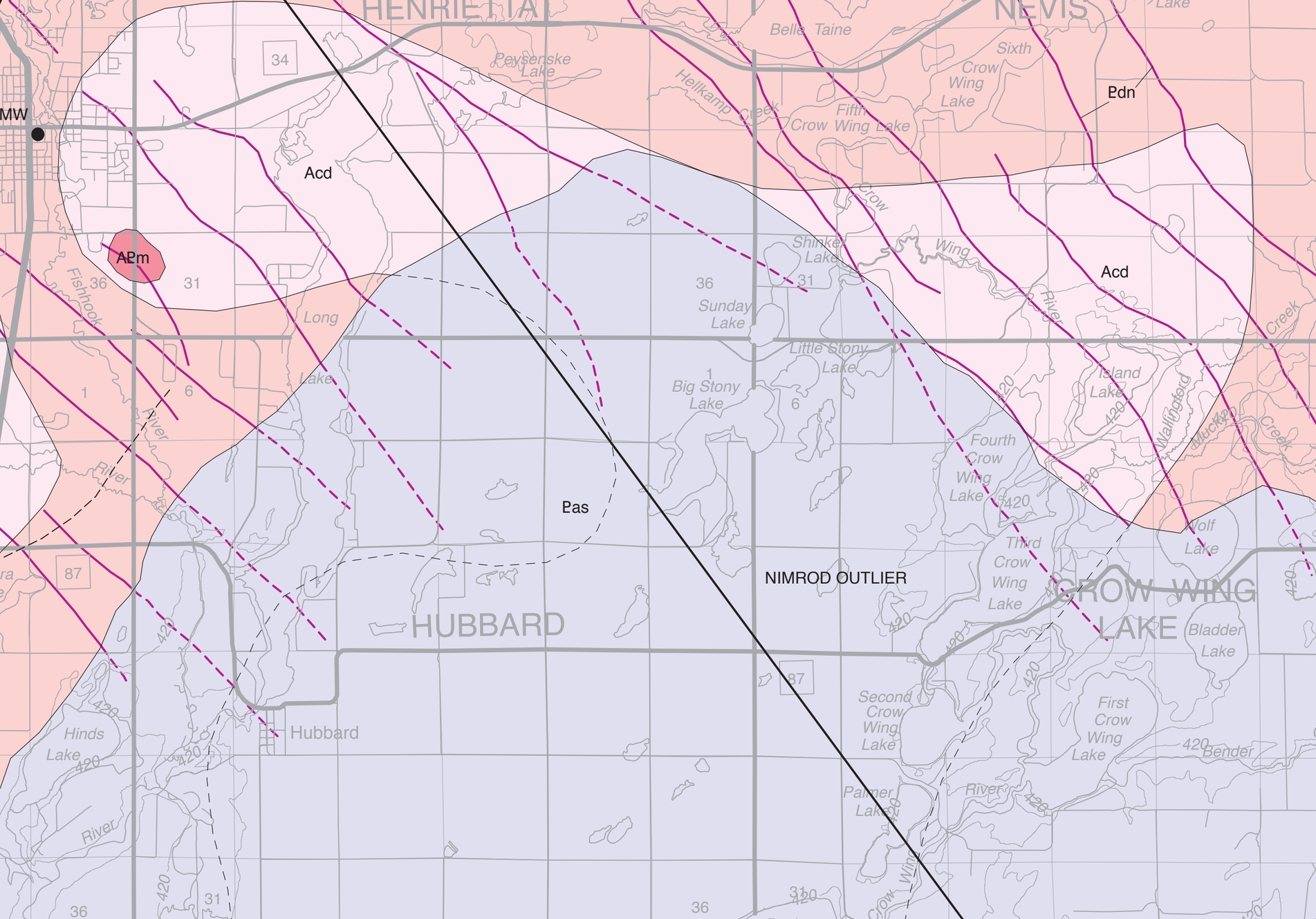

Figure 1. Geophysical map of the Hubbard County area and cross sections (A–A', B–B') derived from geophysical models. The map shows superimposed geophysical images of first vertical derivative magnetic anomaly data (gray scale) and second vertical derivative gravity data (color scale). The range of first 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/km². White lines represent geologic contacts (thin) and faults (thick), all in Archean rocks. Teeth on thrust faults are on the upthrown block. The thin black lines, which trend typically northwest, represent the trajectories of Paleoproterozoic diabase dikes (units Ᵽdn, Ᵽdr) based on linear magnetic anomalies. The dashed white line represents the interpreted extent of the Nimrod outlier, a basin of Paleoproterozoic sedimentary rocks that are correlated with the Animikie Group. Archean contacts and Paleoproterozoic dikes are inferred to extend beneath the Nimrod strata on the basis of geophysical data. Cretaceous strata are not portrayed because they are essentially transparent to the geophysical methods employed here. Bold white lines labeled A–A' and B–B' represent the locations of the cross sections.

The cross-sections (A–A', B–B') depict subsurface structure based on the modeling of gravity and magnetic data. The portrayal of unit colors, contact lines, and dike trajectories on the cross sections are the same as those used for the geologic map. Faults are shown as thick black lines, and the interpreted direction of primary movement is indicated by arrows for the Leech Lake Structural Discontinuity. Dashed white lines are model-based boundaries between bodies that show geophysical contrasts within a map unit. These probably represent slight variations in rock composition, and may be an indication of the trend of layering or other foliation within the rock. No vertical exaggeration is shown, which renders the land surface nearly horizontal at this scale.

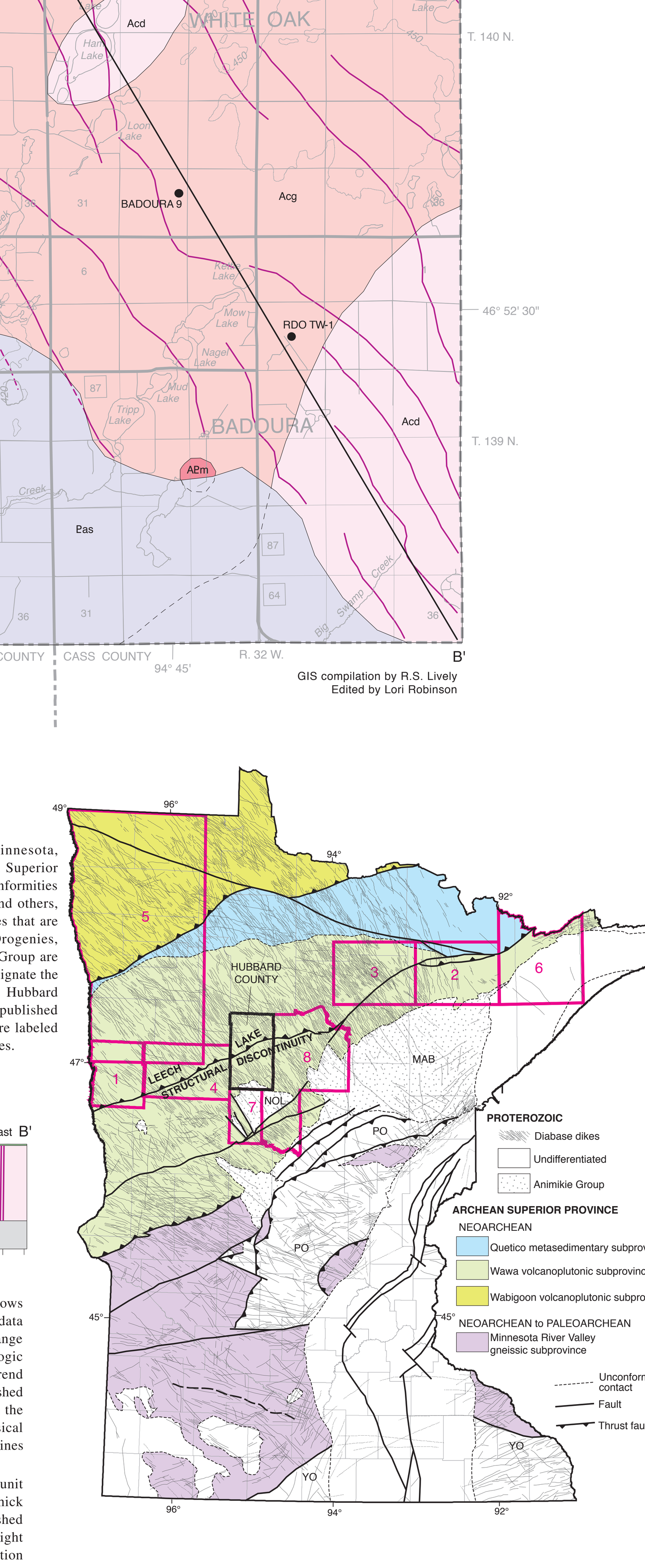

Figure 2. Generalized bedrock terrane map of Minnesota, showing the location of subprovinces of the Archean Superior Province (in color) and major bounding faults and unconformities of Archean to Proterozoic age (modified from Jirsa and others, 2011). PO and YO designate Paleoproterozoic terranes that are closely associated with the Penokean and Yavapai Orogenies, respectively. Paleoproterozoic strata of the Animikie Group are indicated by the stipple pattern, and MAB and NOL designate the main Animikie basin and Nimrod outlier, respectively. Hubbard County is outlined in black. Magenta outlines show published maps mentioned and cited in the Introduction—they are labeled using numbers that correspond to those in the references.