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Harvey Thorleifson, Director

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COUNTY ATLAS SERIES
ATLAS C-31, PART A
Morrison County
Plate 2—Bedrock Geology

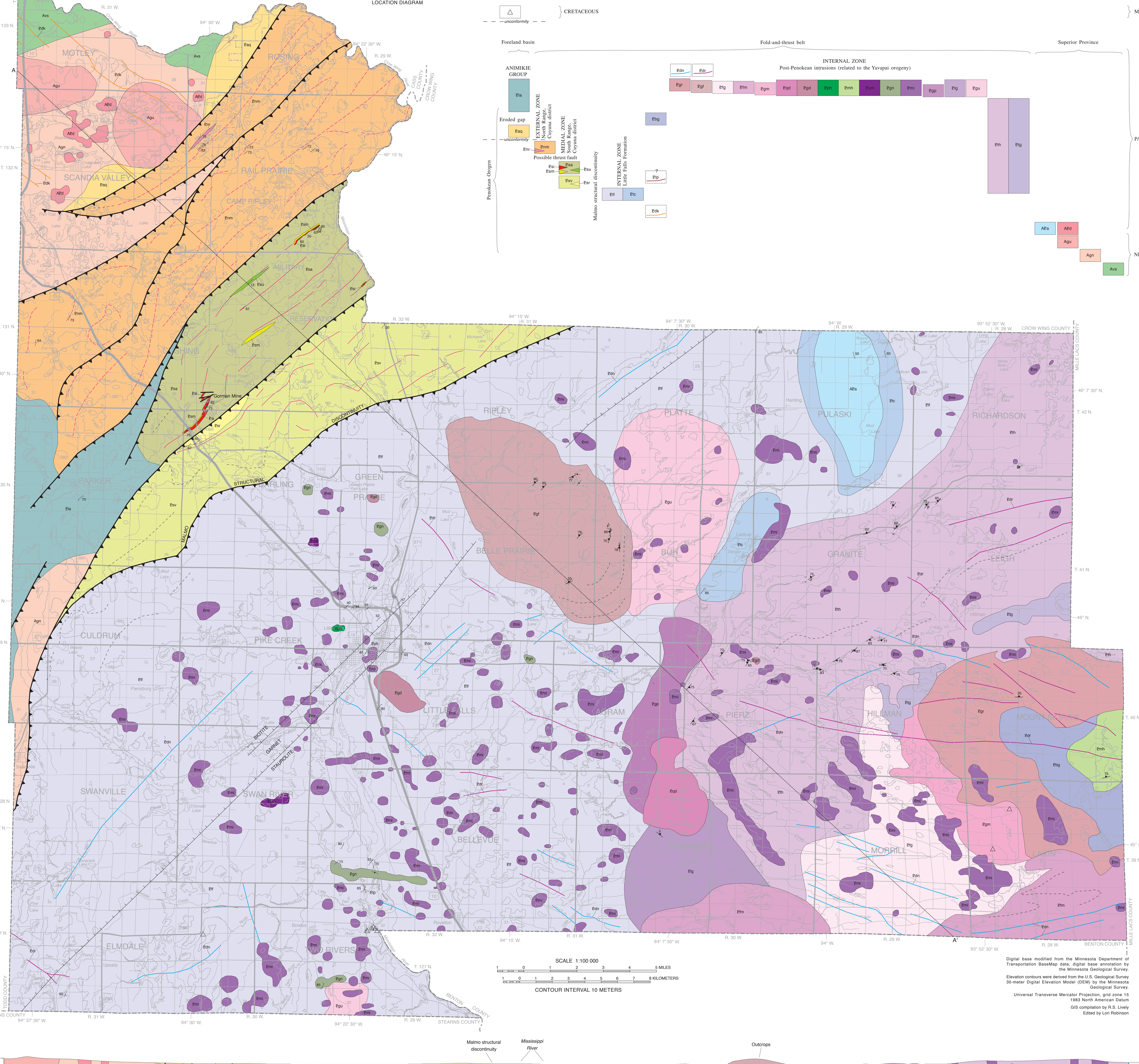
BEDROCK GEOLOGY

By

Terrence J. Boerboom

2014

CORRELATION OF MAP UNITS

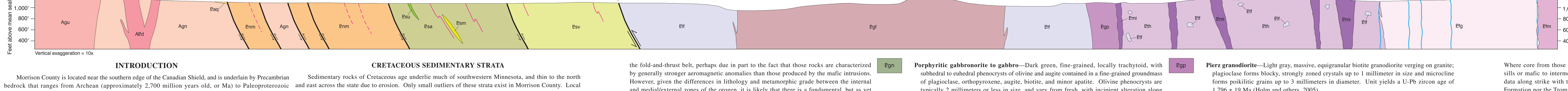


Digital base modified from the Minnesota Department of Transportation BaseMap data; digital base annotation by the Minnesota Geological Survey.

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

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



MAP SYMBOLS

Inferred contact—Mainly located from aeromagnetic data, except where locally controlled by information from drill holes, drilling logs, and bedrock outcrops.

Inferred fault—Mainly interpreted from aeromagnetic data but locally based on drill-hole data.

Inferred thrust fault or structural discontinuity—Sawteeth on upper plate. Interpreted to have mainly north-directed thrust displacement; position located from aeromagnetic data.

Sharp linear positive aeromagnetic anomaly—Probably indicative of iron-formation.

Broad linear positive aeromagnetic anomaly—Possibly indicative of iron-formation.

Linear positive aeromagnetic anomaly.

Approximate metamorphic isograd in the Little Falls Formation—Teeth point towards lower metamorphic grade; metamorphic zones are indicated by mineral names.

45 75 **Bedding**—Showing strike and dip: inclined, vertical. Ball indicates upright topping direction where known. Dip direction in drill cores is largely unknown and are assumed everywhere to dip to the southeast, as shown on historic drilling cross-sections at some locations.

60 **Overturned bedding**—Showing strike and dip; this example shows bedding whose younging direction is north but which dips south.

60 **Metamorphic foliation**—Showing strike and dip: inclined, vertical.

60 **Igneous foliation**—Showing strike and dip: inclined, vertical alignment of magmatic minerals and autoliths.

Bedrock outcrop.

Location of outcrop or drill hole that intersected Cretaceous sedimentary strata—Typically less than 5 feet (1.5 meters) thick.

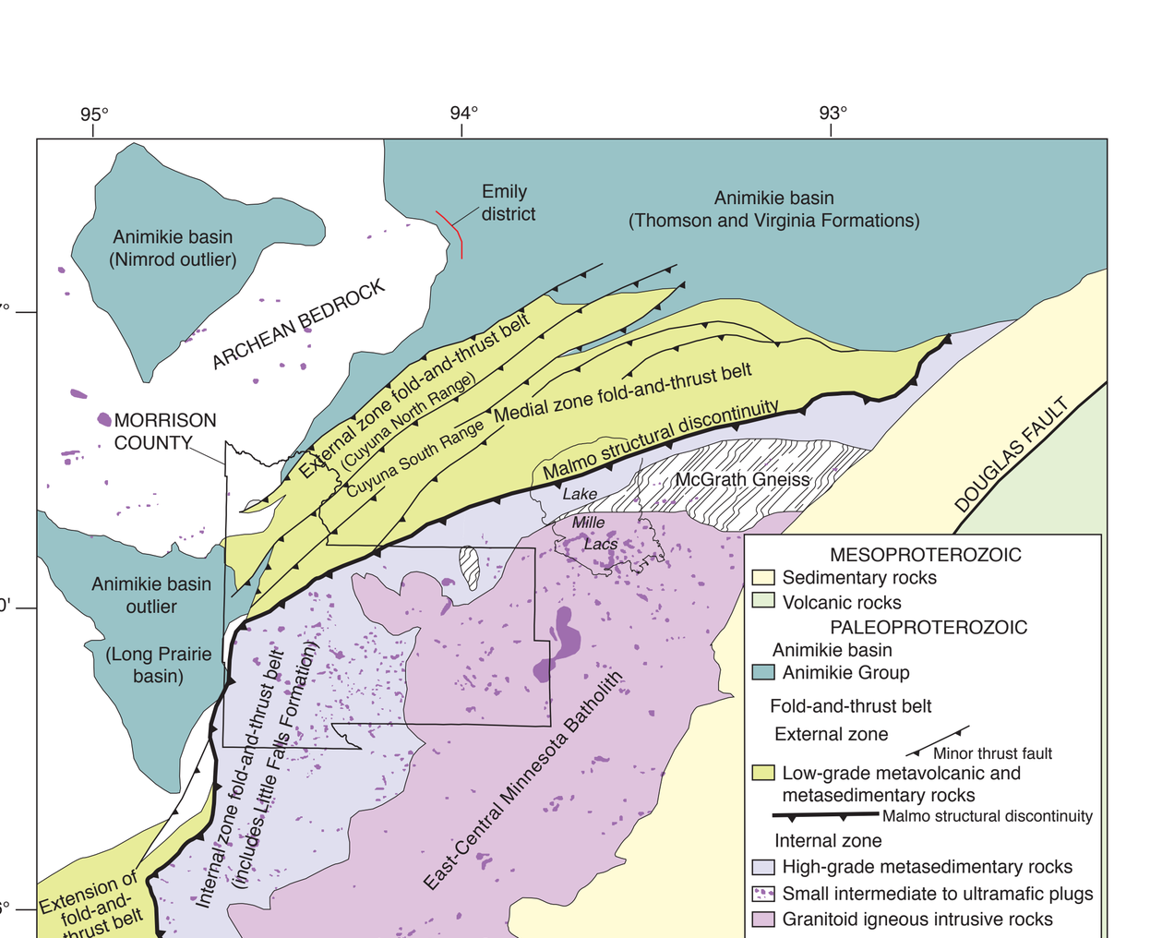


Figure 1. Simplified geologic map of east-central Minnesota showing the major structural elements of Paleoproterozoic rocks of the Penokean Orogen and Archean Superior Province.

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INTRODUCTION

Morrison County is located near the southern edge of the Canadian Shield, and is underlain by Precambrian bedrock that ranges from Archean (approximately 2,700 million years old, or Ma) to Paleoproterozoic (approximately 2,200 to 1,800 Ma) in age (Fig. 1). In places the Precambrian bedrock is overlain by thin erosional remnants of Cretaceous (approximately 90 Ma) sedimentary rocks, the distribution of which is poorly understood due to lack of exposures.

Most of the bedrock is covered by glacial sediment; however, scattered bedrock outcrops are present in and near the town of Randall, along and near the Mississippi River near Little Falls and Royalton, and throughout the county east of the Mississippi River.

In addition to the bedrock exposed in outcrops, many exploratory drill holes have been placed in the county. Early drilling efforts up until about 1950 were aimed entirely at exploring for iron; these drill holes were located from the vicinity of Randall northward into Cushing and Scandia Valley Townships. More recently, several drill holes were placed into the part of the county south and east of Randall as part of regional mineral exploration programs by various companies searching for diamonds and base metals, and others for scientific research. All of the drill cores and cuttings from these more recent drilling programs, and from much of the pre-1950s drilling, are stored at the core library operated by the Minnesota Department of Natural Resources—Division of Lands and Minerals, in Hibbing. All but four of the available cores and cuttings (approximately 85 holes) were examined for this project and used to help interpret the bedrock geology. Drill cores from most of the pre-1950s drill holes were not preserved: however, in most cases drilling logs and maps showing the locations of the drill holes are available. Although most of these drill logs contain only rudimentary lithologic descriptions, they commonly contain iron assay data that are useful for delineating iron-formations. In areas between drill holes and bedrock outcrops, the bedrock geology is inferred, with varied degrees of confidence, from geophysical data.

Prior to construction of this map, the most recent bedrock geologic map that included Morrison County was a regional compilation by Southwick and others (1988), and the northeastern corner of Morrison County is included on a regional compilation map by Boerboom and others (1999). Morrison County is also included in a recent statewide compilation geologic map (Jirsa and others, 2011).

GEOLOGIC SETTING AND HISTORY

ARCHEAN BEDROCK

Bedrock of Archean age, located at the southern margin of the Superior Province, is defined almost entirely on the basis of geophysical data. It is restricted to the northwest corner of Morrison County and a small area along the western border. Essentially no drilling information exists in this part of the county, and bedrock exposures are nonexistent, thus the geology is inferred by extension of bedrock units into the county from adjacent areas where limited drilling information has helped to define the basic geologic framework. The types of Archean bedrock inferred on this basis to exist in Morrison County are composed of metamorphosed sedimentary and volcanic rocks, gneissic tonalite, and granite.

PALEOPROTEROZOIC BEDROCK

Most of Morrison County is located within the Paleoproterozoic Penokean Orogen, a term that refers to a belt of variably deformed and metamorphosed rocks that ranges in age from approximately 2,100 to 1,800 Ma, and extends from central Minnesota eastward to Michigan (Southwick and others, 1988). The rocks were deformed and metamorphosed during the Penokean Orogeny at approximately 1,830 Ma, and were also affected by metamorphism that accompanied voluminous intrusive magmatic activity associated with the Yavapai Orogeny at approximately 1,760 Ma (for example Holm and others, 2007b).

In Minnesota, rocks of the Penokean Orogen are subdivided into two major groups: an older series of deformed and metamorphosed rocks that lie within the fold-and-thrust belt to the south, and a slightly younger series of relatively flat-lying and less deformed rocks that lie within the Animikie basin (Fig. 1) and are collectively termed the Animikie Group. The fold-and-thrust belt is further subdivided into the internal, medial, and external zones. The internal zone contains supracrustal rocks metamorphosed under amphibolite-facies conditions, several large, mostly post-tectonic intrusions of dominantly granitic composition, and hundreds of small, post-tectonic, generally mafic to ultramafic intrusions. In contrast, the medial and external zones lack any significant intrusive rocks and contain several sub-panels dominated by volcanic and sedimentary rocks, including thin iron-formations, which are generally metamorphosed under only greenschist-facies conditions. For a complete synopsis of the geologic evolution of the fold-and-thrust belt and Animikie basin refer to Southwick and others (1988, 2001), Southwick and Morey (1991), and Morey and Southwick, (1995).

Although all the deformation and metamorphism of Paleoproterozoic bedrock in the Penokean Orogen has traditionally been attributed solely to the Penokean Orogeny, recent geochronologic studies show that rocks in both the internal and external zones of the fold-and-thrust belt were metamorphosed as recently as 1,760 to 1,770 Ma. This compares with emplacement ages of the granitic rocks in southeastern Morrison County that range from 1,776 Ma to 1,800 Ma, indicating that the metamorphism may be attributed to widespread crustal thickening and heating related to pluton emplacement. These metamorphic and pluton emplacement ages correspond to the Yavapai Orogeny, a post-Penokean collisional event focused south of the Penokean Orogen (Schneider and others, 2004; Holm and others, 2007a, b; Van Schmus and others, 2007). Similar studies have shown that sediment deposition into the upper part of the Animikie basin in Ontario continued until at least 1,777 Ma (Heaman and Easton, 2005), during the time of the Yavapai Orogeny.

Malmo structural discontinuity

The Malmo structural discontinuity is interpreted to be a thrust fault that trends southwestward through Morrison County (Fig. 1). This discontinuity is a major structural feature that juxtaposes lower to middle crustal-level rocks in the internal zone of the Penokean Orogen (the Little Falls Formation) against upper level supracrustal rocks in the external zone of the orogen (the Cuyuna South Range). In Morrison County the Malmo structural discontinuity is well demarcated by the abrupt truncation of positive aeromagnetic anomalies produced by the iron-formations in the South Range by the featureless aeromagnetic pattern of the Little Falls Formation to the south.

CRETACEOUS SEDIMENTARY STRATA

Sedimentary rocks of Cretaceous age underlie much of southwestern Minnesota, and thin to the north and east across the state due to erosion. Only small outliers of these strata exist in Morrison County. Local exposures of these rocks occur near the confluence of the main Two River channel and the Mississippi River (Upham, 1888; Stauffer and Thiel, 1941). Shale, sandstone, and minor lignite host freshwater fossils, and shark teeth have also been found. A Cenomanian age (93.5 to 99.6 million years) has been assigned to these rocks (Merewether, 1983). Similar rocks have been intersected by a few wells in the county, with a maximum thickness of 10 feet (3 meters).

DESCRIPTION OF MAP UNITS

PALEOPROTEROZOIC TO MESOPROTEROZOIC ROCKS

Diabase dikes—Several normally and reversely-polarized diabase dikes of unknown width are inferred on the basis of weak linear positive and negative aeromagnetic lineaments, within the internal zone of the Penokean Orogen. Aeromagnetic data indicate that these dikes post-date the main granitoid plutonism in the area; on the basis of studies elsewhere, the normally polarized dikes are likely to be close in age to the Yavapai plutonic rocks, whereas the reversely-polarized dikes may be either Paleoproterozoic in age, or far-reaching dikes related to younger Mesoproterozoic magmatic activity to the east (Fig. 1; Boerboom, 2009).

Ᵽdn **Diabase dike, normally polarized**—Inferred from isolated linear positive aeromagnetic anomalies. Not exposed in outcrops or intersected in drill cores.

Ᵽdr **Diabase dike, reversely polarized**—Inferred from isolated linear negative aeromagnetic anomalies. Not exposed in outcrops or intersected in drill cores.

PALEOPROTEROZOIC ROCKS

The terminology for metamorphic rocks on this map utilizes the term *meta* as a prefix to the protolith, for example metamorphosed graywacke is called metagraywacke, metamorphosed basalt is termed metabasalt, etc. In instances where the metamorphic grade is high enough to have caused substantial recrystallization the terms *phyllite* or *schist* may be used, with mineralogic modifiers such as garnet, biotite, or staurolite.

Animikie Group—The Animikie Group in Morrison County is comprised of the Long Prairie basin (Southwick and others, 1988) and rocks thought to be equivalent to the Pokegama Quartzite. The Long Prairie basin is considered to represent an outlier or erosional remnant of a larger, formerly continuous basin that also includes the Nimrod outlier to the north, and the main Animikie basin to the northeast (Fig. 1), where a thick slate-graywacke sequence (the Virginia and Thomson Formations) overlies the Biwabik Iron Formation, which in turn overlies the Pokegama Quartzite. Limited drilling information over the Long Prairie basin, along the western edge of Morrison County, indicates that it is composed of slate and graywacke typical of the Animikie basin in general. Small erosional and structural remnants of the Pokegama Quartzite, which comprises the lowermost strata of the main Animikie basin, are inferred from drill core and geophysical data to be present in Morrison County adjacent to the north edge of the Cuyuna North Range (Fig. 1).

Ᵽaq **Pokegama Quartzite**—Gray quartzite, quartz-rich mudstone, arkosic sandstone, and conglomerate, inferred to extend westward from the Emily district in Crow Wing County (Boerboom and Chandler, 2004) to its western terminus in Morrison County on the basis of two drill cores. A drill core from the north edge of T. 133 N., R. 30 W., sec. 29 is composed of gray to reddish-brown, massive, fine-grained arkosic sandstone that contains abundant microcline and plagioclase feldspar. Another drill core located in T. 132 N., R. 31 W., sec. 21, NW encountered a coarse-grained polymict lithic conglomerate containing cobbles of dominantly metagraywacke, as well as meta-argillite and siltstone, rhyolite, andesite, and biotite-chlorite schist. The cobbles are stretched into a subvertical plane and range from 1 to 20 centimeters in size, but are mostly in the 2 to 3 centimeter range; they were most likely derived from rocks of the Penokean fold-and-thrust belt to the south (Southwick and others, 1988). The Pokegama Quartzite here is inferred to unconformably overlie the Archean basement to the north, but the structural relationships with the adjacent Cuyuna North Range are poorly constrained, and the thrust fault contact shown is conjectural.

Ᵽla **Slate and metagraywacke of the Long Prairie basin**—Gray, laminated phyllitic argillite, siltstone, and graywacke metamorphosed under lower greenschist-facies conditions. Steeply dipping phyllitic foliation is axial-planar to small folds and disruptions in finely laminated bedding. The greater extent of this unit west of Morrison County is well constrained by flat and featureless aeromagnetic anomaly patterns, but near the eastern edge of Morrison County the details of the relationships with Cuyuna Range strata are somewhat conjectural.

Fold-and-thrust belt—Internal zone intrusive igneous rocks: Ultramafic to intermediate intrusive rocks—More than 200 generally small, mostly mafic to ultramafic plug-like intrusions (units Ᵽgd, Ᵽph, Ᵽmh, Ᵽmi, Ᵽum, and Ᵽgn) that are generally 0.02 to 1.2 square miles (12 to 750 acres) but as much as 3 square miles (2,000 acres) in size, are peppered throughout the southeastern half of the county. Related to these is a larger dioritic intrusion (the Buckman intrusion—unit Ᵽqd). These intrusions form prominent positive aeromagnetic anomalies, particularly where they have intruded into the magnetically featureless Little Falls Formation. Although smaller intrusions are rarely coincident with gravity stations, the larger intrusions produce sharp positive Bouguer gravity anomalies.

Several of these bodies have been drilled, one for scientific drilling purposes, others in the 1980s by Exmin Corporation in search of diamonds, and more recently by Kennecott Exploration in search of base metals, and four are known to be exposed in surface outcrops. These small intrusions are present throughout the internal zone of the Penokean Orogen beyond Morrison County (Fig. 1), but none have been identified in the medial or external zones of the fold-and-thrust belt, perhaps due in part to the fact that those rocks are characterized by generally stronger aeromagnetic anomalies than those produced by the mafic intrusions. However, given the differences in lithology and metamorphic grade between the internal and medial/external zones of the orogen, it is likely that there is a fundamental, but as yet not understood, reason why the mafic intrusions are confined to only the high-grade internal zone.

This suite of intrusions is likely magmatically related, and phases or dikes of felsic composition occur locally in rocks of mafic to ultramafic composition. The range of compositions may be the result of varied degrees of contamination by melting of preexisting crustal rocks, where the ultramafic compositions (for example, unit Ᵽum) represent the least-contaminated, mantle-derived magmas and the felsic end-members (for example, unit Ᵽgd) represent magmas that have assimilated greater amounts of melted crust. Age dates on two of these bodies using the Ar-Ar method yield ages of 1,791 ± 8 Ma and 1,770 ± 6 Ma (Jirsa and others, 2006). Although these ages should be considered a minimum because of the method used, they indicate that these bodies are likely coeval with the main Yavapai-age phase of granitic plutonism in east-central Minnesota.

Ᵽgd **Granodiorite, diorite, and tonalite**—Gray, medium- to coarse-grained, massive. A drill core from the rock body north of Little Falls is composed of equigranular biotite tonalite verging on quartz diorite that contains 56 percent strongly zoned plagioclase, 21 percent biotite, 16 percent quartz, 2 percent chlorite, 3 percent epidote, 1 percent hornblende, and minor apatite, oxides, and magmatic calcite. The larger intrusion located at the southeast outskirts of Little Falls, as inferred from a single, short drill core, is composed of porphyritic, biotite-bearing, hornblende granodiorite verging on tonalite that contains 38 percent strongly zoned, mostly euhedral plagioclase up to 2 millimeters in size, 26 percent euhedral, strongly zoned, dark green hornblende phenocrysts and crystal clusters up to 5 millimeters in size, 16 percent anhedral-interstitial quartz, 15 percent biotite, 4 percent microcline, 1 percent oxides, and trace amounts of magnetite, anhedral-interstitial calcite, chlorite, apatite, muscovite, epidote, and actinolite. These intrusions are similar to small sills and segregations associated with units Ᵽum and Ᵽgn, as well as the more felsic end-member of unit Ᵽph, and may represent magma from the same source that was more highly contaminated by assimilation of the Little Falls Formation country rock at depth.

Ᵽph **Hornblendite to granodiorite**—Dark green, medium-grained, composed of 69 to 95 percent sub-euhedral, green hornblende up to 6 millimeters in size, generally small amounts but locally as much as 25 percent augite, trace to 2 percent biotite, 0 to 5 percent altered plagioclase, and trace amounts of oxides, chlorite, actinolite, apatite, sphene and magnetite calcite. Locally grades into biotite-augite-bearing hornblende granodiorite to diorite similar to unit Ᵽgd. A small intrusion is exposed northwest of Little Falls, and in a 10-foot (3-meter) wide, approximately north–south-trending dike that cuts the Little Falls Formation, exposed just below the Little Falls Dam on the east bank of the Mississippi River. Identical 1.6- to 3-foot (0.5- to 1-meter) thick intervals are also present in some of the drill cores in unit Ᵽgn.

Ᵽmh **Hornblende gabbro**—Dark green, medium- to coarse-grained, strongly foliated and variably lineated, weakly plagioclase-phyric. The typical phase is composed of approximately 70 percent hornblende as prismatic crystals up to 1 centimeter in length, 25 percent semi-blocky, weakly zoned labradoritic plagioclase and rare small plagioclase phenocrysts, 3 to 4 percent magnetite, up to 2 percent biotite that ranges from small anhedral grains to centimeter-sized poikiloblasts, and minor epidote. Locally contains pegmatitic clots of feldspar with coarse-grained green biotite, and others composed of pyrite, biotite, hornblende, and feldspar. Magmatic-trachytoid foliation, defined by aligned acicular hornblende, dips 70° to 85°. Cut by thin, comagmatic diorite to tonalite dikes that contain relatively abundant zircon grains, and later-emplaced fine-grained porphyritic mafic dikes with aphanitic chilled margins; the latter contains tiny trachytoid plagioclase phenocrysts and 1- to 3-millimeter euhedral talcose pseudomorphs of olivine, in a semi-opaque aphanitic matrix that is likely devitrified glass. The chilled dikes are possibly related to similar thin dikes noted in the southern portion of Carlton County (Boerboom, 2009) to the east. Unit extent is based on a single drill core combined with prominent, coincident positive gravity and aeromagnetic anomalies.

Ᵽum **Ultramafic pyroxene-olivine hornblendite**—Dark green, coarse-grained, phlogopitic; alternatively termed olivine clinopyroxenite (Southwick and Chandler, 1987) on the basis that the amphiboles may be late-magmatic secondary replacement products of earlier augite. Composed of 30 to 39 percent poikilitic, pargasitic to magnesio-hastingsitic hornblende, which typically exhibits pale reddish-brown cores and pale green rims, 28 to 36 percent olivine (variably altered to a mixture of serpentine, talc, tremolite, and iddingsite), 13 to 20 percent augite, 2 to 8 percent phlogopite, 1 to 15 percent secondary actinolitic amphibole, 3 to 6 percent opaque oxides that are largely secondary by-products of olivine alteration, 0 to 2 percent chlorite, and trace amounts of chromite, apatite, and other microscopically unidentifiable secondary alteration products. Probe analyses yield Mg numbers (Mg/[Mg + Fe]) of 0.87 (olivine), 0.86 (augite), 0.82 (pargasitic hornblende), and 0.88 (phlogopite), and two whole-rock analyses from core P-14B yield Mg numbers of 0.83, with high values of Cr (2,540 to 2,800 parts per million), Ni (770 to 796 parts per million), and MgO (25.5 to 26.8 weight percent).

Most of these intrusions are associated with fine-grained porphyritic gabbro to gabbronorite (unit Ᵽgn), which in some cases is clearly intrusive into, but most likely comagmatic with, the coarse-grained ultramafic phase. Thin comagmatic, felsic pegmatitic segregations, composed of very coarse-grained phlogopite in a white feldspathic matrix, are common; these zones grade abruptly into the adjacent hornblendite. Southwick and Chandler (1987) utilized three-dimensional magnetic modeling techniques to interpret the shape of some of these intrusions as pipe-shaped bodies that plunge 80° to the north, and extend between 0.9 and 1.9 miles (1.5 and 3.1 kilometers) beneath the land surface.

Ᵽgn **Porphyritic gabbronorite to gabbro**—Dark green, fine-grained, locally trachytoid, with subhedral to euhedral phenocrysts of olivine and augite contained in a fine-grained groundmass of plagioclase, orthopyroxene, augite, biotite, and minor apatite. Olivine phenocrysts are typically 2 millimeters or less in size, and vary from fresh, with incipient alteration along rims and cracks, to nearly completely replaced by mixtures of tremolite, talc, and iddingsite. Augite phenocrysts are typically up to 4 millimeters in size, generally more abundant than olivine, are not altered, are typically zoned, and commonly composed of mosaics whose overall shape defines a uniform phenocryst. The groundmass plagioclase ($Ab_{49-50}An_{47-50}Or_{1-5}$; andesine to labradorite) is tabular, fresh, and weakly zoned; orthopyroxene (bronzite, Mg# 0.78) forms granular, pink to green pleochroic granules, as does pale green augite. Biotite is late-crystallized, poikilitic, and varies in size from small, irregular grains to irregular books up to 1.5 centimeters in length. Anhedral-interstitial alkali feldspar ($Ab_{23}An_8Or_{69}$) is common, as are minor amounts of apatite.

This unit is exposed south of Blanchard Dam near Royalton; these outcrops are inferred from aeromagnetic data to be in the same body as in drill cores located 1.6 miles (2.6 kilometers) to the west. Intrusive contacts (seen only in drill cores) with the adjacent Little Falls Formation (unit Ᵽlf) are commonly highly altered and difficult to characterize, but in one core a sharply chilled contact is well preserved as chilled mafic rock with altered augite phenocrysts in a fine-grained groundmass, and the schist adjacent to the contact shows evidence of local partial melting. Several of the southernmost drill cores in this unit contain scattered xenoliths of staurolite schist and former euhedral staurolite crystals now composed of hercynitic spinel, corundum, and alkali feldspar; apparently the staurolite crystal pseudomorphs remained as refractory xenocrysts left behind after assimilation of the surrounding schist into the mafic magma. The spinel-corundum assemblage after staurolite is also present in the wall rock adjacent to the intrusions; whereas garnet in the same schist was apparently stable under the conditions of thermal metamorphism imposed on the wall rocks by the intrusions. Interestingly, the presence of orthopyroxene in mafic intrusive rocks is attributed to the assimilation of aluminum-rich sedimentary rocks by basic magma (Deer and others, 1966, p. 113). It is speculatively proposed that an originally ultramafic magma (such as unit Ᵽum) may have assimilated the pelitic Little Falls Formation at depth to produce these porphyritic gabbronorites, and that some of the ultramafic magma may have quickly passed through the schist to produce the ultramafic intrusions, followed closely by emplacement of the contaminated gabbronorite bodies, in some cases along the same conduits.

Ᵽmi **Mafic to intermediate intrusions, undifferentiated**—Mapped solely on the basis of small, high-amplitude, positive aeromagnetic anomalies. Based on the size and shape of these anomalies, they are inferred to be composed of ultramafic, mafic, and intermediate-composition intrusions similar to units Ᵽgd, Ᵽph, Ᵽmh, Ᵽum, and Ᵽgn.

Fold-and-thrust belt—Internal zone intrusive igneous rocks: Intermediate to felsic intrusive rocks—The bedrock in the east side of Morrison County is composed primarily of a series of granitic to dioritic plutons, which collectively form the northwestern margin of a larger mass of intrusions known informally as the East-Central Minnesota Batholith (Fig. 1). The oldest known of these intrusions, the Bradbury Creek granodiorite (unit Ᵽbg), yields U-Pb zircon ages of 1,858 ± 11 and 1,877 ± 15 Ma, which indicate it was emplaced during the late stages of the Penokean Orogeny, consistent with the observation that it contains a tectonically-imposed foliation related to Penokean deformation and metamorphism.

The rest of the intrusions in Morrison County that have been dated are post-Penokean, emplaced between 1,800 and 1,766 Ma, a time interval that corresponds to crustal convergence related to the younger Yavapai Orogeny.

Ᵽgr **Porphyritic biotite granite**—Grayish-pink to black and pink, coarse-grained, with approximately 25 percent blocky microcline phenocrysts up to 7 centimeters in length as well as scattered, smaller, blocky white plagioclase phenocrysts. Also contains quartz, approximately 5 percent biotite, and accessory zircon, apatite, and oxides. Based on a single drill core, coupled with low- to moderate-amplitude aeromagnetic and generally low gravity signatures. Unit yields a U-Pb age of 1,766 ± 8 Ma (Holm and others, 2005).

Ᵽgf **Freedhem granodiorite**—A multi-phase intrusion composed mainly of dark gray, medium-grained, hornblende-biotite granodiorite and comagmatic pink hornblende-biotite quartz monzonite to granite. Later pink phases range from sharp dikes to blebs and stringers mixed with the gray phase; larger masses of this phase are trachytoid and contain centimeter- to decimeter-sized inclusions of the gray phase that are elongate parallel to the magmatic fabric. The overall shape and size of this intrusion is well constrained by a pronounced positive aeromagnetic anomaly and corresponding positive gravity anomaly. U-Pb zircon ages from the main phases of the granodiorite are 1,775 ± 3 and 1,776 ± 7 Ma, and on a pink phase, 1,773 ± 2 Ma (Holm and others, 2005).

Ᵽfg **Foley Granite**—Pink to salmon, coarse-grained, biotite- and hornblende-bearing, intruded by small dikes of porphyritic granite and aplite. Extended into this map area, on the basis of aeromagnetic data, from areas south of the county where it is better exposed and mapped; also intersected in one drill hole at the southern edge of the county (Jirsa and others, 2003). Unit yields a U-Pb age of 1,779 ± 4 Ma (Holm and others, 2005).

Ᵽfm **Foley Granite, magnetic phase**—Variably magnetic zones macroscopically similar to unit Ᵽfg. Extended into this map area, on the basis of aeromagnetic data, from areas south of the county where it is relatively well exposed and mapped (Jirsa and others, 2003).

Ᵽgm **Weakly porphyritic biotite granite, moderately magnetic**—Gray to pinkish-gray, coarse-grained, in addition to coarse-grained microcline, plagioclase, and quartz, contains approximately 4 percent biotite and accessory apatite, oxides, zircon, chlorite, and muscovite. Based on a single drill core that is essentially identical to drill core in unit Ᵽgr, but delineated on the basis of a positive aeromagnetic anomaly pattern. Unit yields a U-Pb age of 1,784 ± 8 Ma (Holm and others, 2005).

Ᵽgp **Pierz granodiorite**—Light gray, massive, equigranular biotite granodiorite verging on granite; plagioclase forms blocky, strongly zoned crystals up to 1 millimeter in size and microcline forms poikilitic grains up to 3 millimeters in diameter. Unit yields a U-Pb zircon age of 1,796 ± 19 Ma (Holm and others, 2005).

Ᵽlg **Hornblende granite**—Pink and black, coarse-grained, with dark gray, fine-grained, comagmatic monzonitic phases. Informally termed the Little Rock pluton (Jirsa and others, 2003).

Ᵽqd **Biotite-pyroxene quartz diorite**—Gray, medium-grained, variably porphyritic; contains thin comagmatic segregations of coarse-grained black and pink granite. The main phase contains an estimated 62 percent fresh, blocky plagioclase, 11 percent poikilitic quartz, 4 to 10 percent poikilitic biotite, 8 to 12 percent granular pyroxene (augite with hypersthene exsolution lamellae, and orthopyroxene), 2 percent hornblende, 2 percent opaque oxides, trace to 1 percent apatite, and trace amounts of zircon and sphene. Plagioclase phenocryst content varies from 0 to 5 percent. Granitic intervals range from 3 to 12 inches (8 to 30 centimeters) thick and are composed of medium- to coarse-grained hornblende-bearing biotite granite. The overall texture and mineralogy of this body is similar to the St. Wendell quartz gabbro (Boerboom and others, 1995). Unit is based on one 40-foot (12-meter) drill core and one set of water well cuttings, combined with a relatively high-amplitude aeromagnetic anomaly that coincides with a pronounced gravity high. Unit is referred to informally as the Buckman intrusion.

Ᵽgu **Granite**—Granite bodies inferred from geophysical data. A small unit located on the south border of the county is defined by coincident gravity and aeromagnetic lows. The large body just east of the Freedhem granodiorite is marked by a diffuse, low-amplitude, positive aeromagnetic anomaly that is slightly higher and more uniform than typical anomaly signatures of the adjacent Little Falls Formation; this occurrence is highly speculative and much or all of the area included in it may actually be composed of the Little Falls Formation.

Ᵽth **Hillman tonalite**—Light to dark gray, medium- to coarse-grained, irregularly layered; contains xenoliths of coarsely-recrystallized biotite-garnet-cordierite schist derived from the Little Falls Formation. The xenoliths are typically angular and the foliation in them is commonly discordant to the regional northeast-striking foliation of the enclosing tonalite, which has commonly been referred to as migmatite or migmatitic tonalite. Although some of the xenoliths have clearly been melted and assimilated to form garnet-rich neosome layers, in general the tonalite contains a porphyritic-trachytoid fabric, indicative of igneous crystallization, which in places is overprinted by a tectonic foliation. Cut by thin dikes of massive to weakly deformed granite pegmatite and aplite. Unit yields U-Pb zircon ages of 1,800 ± 4 to 1,792 ± 7 Ma (Holm and others, 2005). This unit is exposed across a broad area in Morrison County, but the exact margins of the body are not exposed and are based on aeromagnetic data. Detailed descriptions and modal analyses of the Hillman tonalite can be found in Raidl (1973).

Ᵽtg **Inclusion-rich Hillman tonalite**—Pinkish-gray, medium-grained, strongly foliated. Lithology is based on a single 10-foot (3-meter) drill core composed of light gray tonalite with partly assimilated inclusions of dark gray, strongly foliated, magnetite-bearing biotite-hornblende schist; the extent is inferred from prominent, smooth, positive aeromagnetic anomalies.

Ᵽlp **Granite pegmatite**—Pink dikes and sills intruded into or melted from the Little Falls Formation (unit Ᵽlf). The largest known and only mapped occurrence is in T. 127 N., R. 29 W., sec. 5, NW, approximately 1 mile (1.6 kilometers) south–southwest of the Blanchard Dam. Drilling and trenching records and correspondence from the 1960s, on file at the Minnesota Department of Natural Resources—Division of Lands and Minerals, report a 5- to 10-foot- (1.5- to 3-meter-) wide dike of beryl- and muscovite-bearing pegmatite said to strike N. 25° W. and dip 75° NE. An adit was placed into the side of this dike, and samples were assayed for beryllium, but the deposit was considered too small and low-grade to be economical. Similar but smaller muscovite-bearing granite pegmatite dikes and veins also were noted in some drill cores in the Little Falls Formation. A similar pegmatite within a unit interpreted as the Little Falls Formation exposed east of this map area yields a muscovite Ar-Ar age of 1,810 ± 2 Ma (Holm and others, 2005).

Ᵽbg **Bradbury Creek granodiorite**—Light gray to pink, medium-grained, weakly gneissic, biotite- and hornblende-bearing granodiorite to tonalite. Gravity expression indicates that more dioritic (mafic) compositions are also present. Exposed just east of Morrison County and extended into the county on the basis of aeromagnetic data. Unit yields a U-Pb zircon ages of 1,877 ± 15 to 1,858 ± 11 Ma (Holm and others, 2005).

Fold-and-thrust belt—External zone, Cuyuna North Range Group—North of the Malmo structural discontinuity (Fig. 1) the bedrock is dominated by low-grade phyllitic schists derived dominantly from fine-grained sedimentary rocks, and lesser proportions of mafic to intermediate volcanic rocks, thin iron-formations, and hypabyssal mafic sills (Southwick and others, 1988).

The Cuyuna North Range includes the former Cuyuna Iron Mining District, located in Crow Wing County, approximately 25 miles (40 kilometers) northeast of Morrison County (Boerboom and Chandler, 2004, and references therein). Strata of the Cuyuna North Range include the lowermost Mahnomen Formation (quartz-rich siltstone, graywacke, and thin iron-formation beds), the Trommald Iron Formation, and the uppermost Rabbit Lake Formation (slaty to phyllitic argillite and graywacke). Unnamed units of mafic volcanic rocks and hypabyssal intrusions are known to be abundant in some areas of the Cuyuna district, mainly near the base of the Rabbit Lake Formation but also within the Mahnomen and Trommald Formations. The relative proportion of mafic to intermediate volcanic rocks is almost certainly higher than is depicted on this map, but due to the lack of geophysical contrast and drilling information, the only place where these are shown as a separate map unit is where they are verified in drill core. In some cases where core is no longer available, old drilling records that note intercepts of "green schist" or "diorite" are also mapped as metavolcanic rocks. Where core from those intervals are available, the rock types are variably schistose mafic sills or mafic to intermediate volcanic rocks. Scattered but locally concentrated drilling data along strike with the Cuyuna Mining District indicate that neither the Rabbit Lake Formation nor the Trommald Iron Formation continue southwest into Morrison County due to erosion of structural troughs, and based on the extension of aeromagnetic anomaly patterns from the Cuyuna Mining District, only rocks correlative with the Mahnomen Formation are present. Rocks in the Cuyuna North Range have been metamorphosed under greenschist-facies conditions.

Ᵽnm **Phyllitic argillite, siltstone, and quartzite**—White to pale gray or greenish-gray, phyllitic to schistose, massive to thinly laminated, commonly with disseminated martite and magnetite grains. Ranges from fine-grained white sericitic quartzite and minor arkose to light gray, thinly laminated argillite; locally contains graded beds and folded bedding. Original company drill logs typically called the unit "quartz slate;" iron content is generally 4 to 8 percent, but locally as high as 15 to 16 percent in some ferruginous layers. Typically contains very fine-grained biotite, and unit quartz grains that may have been derived from a felsic volcanic source. Thin, discontinuous iron-formation layers are interpreted from linear positive aeromagnetic anomalies, similar to those to the northeast in Crow Wing County that have been confirmed to be iron-formation by drilling (Boerboom and Chandler, 2004).

Ᵽnr **Rhyolite**—Pink, porphyritic, weakly schistose. Contains scattered, 1- to 2.5-millimeter, slightly recrystallized quartz phenocrysts and 1- to 3-millimeter feldspar phenocrysts that are broken and slightly strung out into the foliation plane, in a matrix of fine-grained quartz and feldspar with minor sericitic muscovite and scattered magnetite crystals. Intersected by a single drill core located near the northern margin of the Cuyuna North Range strata.

Fold-and-thrust belt—Medial zone, Cuyuna South Range Group—The Cuyuna South Range is composed predominantly of phyllitic to weakly schistose, locally graphitic metasedimentary rocks, but also contains a significant but unknown proportion of mafic to intermediate volcanic rocks and hypabyssal intrusions, and numerous thin iron-formations (Southwick and others, 1988). As in the North Range Group, the mafic rocks are shown only where verified by drill core, or in some cases where old drilling records indicate they may exist. Aeromagnetic anomalies produced by the iron-formations in the South Range are relatively high-amplitude with steep gradients, and compared to the anomalies associated with the North Range, are more linear and continuous. Rocks in the Cuyuna South Range have been metamorphosed under greenschist-facies conditions.

Ᵽsa **Metasedimentary rocks**—Fine-grained, phyllitic to schistose slate, argillite, and siltstone; includes an unknown quantity of mafic hypabyssal intrusive and volcanic rocks. The few available core samples are composed of fine-grained, locally graphitic, phyllitic fine-grained metasedimentary rocks ranging to lesser proportions of fine-grained micaceous quartzite, and red-tinted phyllitic rocks, or "ferruginous slate," that approaches iron-formation in composition (15 percent iron). Typically contains fine-grained biotite, sericite, quartz, and small blocky martite grains, and rocks in some core pieces exhibit a strong crenulation cleavage. Referred to as schist (yellow, pink, green), or slate on old exploration logs. Where in proximity to known mafic intrusive or volcanic rocks, the rocks described as "green schist" are included with the thin volcanic units.

Ᵽsi **Silicate-facies iron-formation**—Red, ochre, or brown where oxidized (the bulk of the unit) to gray where unoxidized; thinly laminated but laminations are obliterated where extremely oxidized. Unoxidized parts are composed dominantly of magnetite, stilpnomelane, and quartz, with lesser proportions of ankerite and minnesotaite. Includes thin intervals of ilmenitic mafic hypabyssal and possibly metavolcanic rocks too thin to portray on the map; old photographs of the Gorman Iron Mine (T. 131 N., R. 30 W., sec. 31) show at least two 3-foot (1-meter) thick, moderate to steeply-dipping, schistose mafic dikes cutting thin-banded iron-formation whose bedding dips near vertically to the southeast. Some samples from waste piles at the Gorman Mine are composed of chert that contains sprays of fine-grained stilpnomelane.

Ᵽsm **Mafic to intermediate hypabyssal sills and metavolcanic rocks**—Green, fine- to medium-grained, massive to schistose. Shown only where known from drill cores. Also shown locally where drill cores along strike were described as "green schist" on old logs. Thin sills and dikes within iron-formation, for example in the Gorman Mine, are not shown. Volcanic rocks contain plagioclase phenocrysts in a matrix of lath-shaped plagioclase, chlorite, epidote, biotite, ilmenite, apatite, and a few amygdules of mixed quartz-biotite-chlorite-carbonate. Metagabbroic sills are medium-grained, composed dominantly of hornblende and actinolite after pyroxene, lath-shaped plagioclase, with lesser proportions of skeletal ilmenite variably altered to leucoxene, biotite, chlorite, epidote, and apatite. Basalt locally contains approximately 1 percent fine-grained, needle-shaped rutile aggregates and trace amounts of tourmaline, and in a separate sample, adularia, rutile, and small, randomly-oriented muscovite books.

Ᵽsu **Mafic to ultramafic schist**—Green, medium-grained, composed of approximately 20 percent colorless hornblende and possible minor Mg-rich pyroxene, 10 percent fibrous tremolitic amphiboles that form epitaxial overgrowths on the hornblende, 68 percent pale green chlorite, 1 to 2 percent oxides, and traces of altered, equant plagioclase. Known only from one drill core; texture indicates it may be a hypabyssal intrusion.

Ᵽsv **Metavolcanic and metasedimentary rocks**—Mafic to intermediate igneous rocks similar to those in units Ᵽsa and Ᵽsr, variably graphitic phyllitic schist, and lean iron-formation; generally similar to unit Ᵽsa but inferred to contain a higher proportion of mafic rocks. Overall this unit is characterized by sharp positive aeromagnetic anomalies inferred to be produced by thin iron-formations (shown as thin red lines) that define crude folds having local north-trending axes, but overall defining a possible northeast-plunging synform when aeromagnetic data east of the county are taken into consideration (Boerboom and Chandler, 2004). Drill core DOT-1 is composed of fine-grained, green, porphyritic, carbonate-altered, possibly amygdaloidal, weakly foliated metabasalt that is composed dominantly of altered plagioclase (phenocrysts and felty groundmass), chlorite, magnetite, ilmenite altered to leucoxene, quartz, epidote, fine-grained sericitic muscovite, and calcite.

Ᵽsr **Porphyritic metabasalt to andesite**—Green, fine-grained, pillowed to fragmental, amygdaloidal, schistose. Outcrops in and near the town of Randall are the type locality of the Randall Formation (Morey, 1978), a designation that has been incorporated into larger units (Southwick and others, 1988). Composed of approximately 5 to 8 percent blocky, 1- to 3-millimeter plagioclase phenocrysts in a groundmass of plagioclase, calcite, leucoxene, magnetite, quartz, chlorite, and minor muscovite. Unit is considered here to be part of unit Ᵽsv, but is shown separately because it is exposed and is the type locality for the Randall Formation.

Fold-and-thrust belt—Internal zone metamorphic rocks—Supracrustal sedimentary rocks in the internal zone are metamorphosed to the amphibolite facies, in contrast to the greenschist facies of metamorphism in the medial and external zones. As described above, the internal zone of the fold-and-thrust belt contains abundant late to mostly post-tectonic ultramafic to granitic intrusions that are related to Yavapai-interval orogenesis, as well as the Penokean-age Bradbury Creek granodiorite (unit Ᵽbg) and small pegmatite bodies (unit Ᵽlp) likely derived by partial melting of the Little Falls Formation (unit Ᵽlf). The northern margin of the fold-and-thrust belt internal zone is marked by the Malmo structural discontinuity (Fig. 1).

Ᵽlf **Little Falls Formation**—Gray, strongly foliated, schistose metagraywacke and argillite. Based on scattered bedrock exposures and drill cores, the Little Falls Formation contains only metamorphic biotite near the Malmo structural discontinuity. The metamorphic grade increases to the southeast away from the Malmo structural discontinuity, through a narrow zone that contains garnet, into a broad zone marked by the assemblage of garnet, sillimanite, and staurolite. Xenoliths of this unit contained within the Hillman tonalite (unit Ᵽth) also contain cordierite. The Little Falls Formation is locally intruded by small dikes and sills of coarse-grained granitic pegmatite (unit Ᵽlp). Geophysically this unit is characterized by a broad, flat, aeromagnetic anomaly pattern and variable gravity anomaly patterns speculatively attributed to igneous intrusive rocks at depth. Depositional age is unknown, but unit yields an Ar-Ar biotite metamorphic age of 1,755 ± 12 Ma (Holm and Lux, 1996), and total Pb monazite metamorphic ages of 1,759 ± 6 to 1,776 ± 4 Ma (Holm and others, 2007b).

Ᵽlc **Layered felsic gneiss**—Gray with pink bands, medium-grained, metamorphically recrystallized. Based on two drill cores, this unit is composed of quartz, plagioclase, biotite, poikilitic cordierite, sillimanite, minor staurolite, muscovite, magnetite, sphene, and zircon. The northern unit that rims unit AᵽPa is interpreted to be a narrow, high-grade metamorphic aureole in the Little Falls Formation (unit Ᵽlf), where it flanks a gneiss dome; the southern unit may also represent a gneiss dome that is not as deeply exhumed by erosion. The extent is based on moderate to high positive aeromagnetic anomalies. Unit yields an Ar-Ar biotite metamorphic age of 1,753 ± 13 Ma (Holm and others, 1998).

Paleoproterozoic diabase dikes

Ᵽdk **Diabase dikes of the Kenora-Kabetogama dike swarm**—Northwest-trending, diabasic to gabbroic dikes of quartz tholeiite composition, typically less than 350 feet (107 meters) wide, recognized on the basis of linear positive aeromagnetic anomalies. Correlative with dikes exposed in northern and southwestern Minnesota and southern Canada that have been dated at 2,076 to 2,077 Ma (Wirth and others, 1995; Buchan and others, 1996; Schmitz and others, 2006). The nearest exposed dike in this swarm is northeast of Staples, in Cass County. These dikes are only present in the northwest corner of the county where the country rock is Archean in age.

PALEOPROTEROZOIC OR ARCHEAN ROCKS

AᵽPa ***Layered hornblende-biotite gneiss***—Gray to greenish-gray, layers vary from hornblende-biotite gneiss to biotite amphibolite, with thin, light gray, feldspathic layers. Composed of varied proportions of biotite, hornblende, plagioclase, and quartz, with minor apatite, zircon, sphene, and Fe-Ti oxides; exhibits equilibrium metamorphic texture with foliation carried primarily by biotite. Unit description is based on a single 10-foot (3-meter) drill core (Southwick and others, 1986) placed into the center of a prominent north–south-trending, positive aeromagnetic anomaly and coincident gravity anomaly, interpreted to be a gneiss dome of possible Archean age, rimmed by unit Ᵽlc. Age is uncertain, but metamorphism at approximately 1,750 Ma is indicated by an Ar-Ar hornblende age of 1,749 ± 16 Ma, and an Ar-Ar biotite age of 1,747 ± 18 Ma (Holm and others, 1998).

AᵽPd ***Mafic intrusion***—Defined on the basis of sharp, moderately high-amplitude aeromagnetic anomalies; no drill core or outcrop is known to exist. May be Paleoproterozoic in age and similar to unit Ᵽmi.

ARCHEAN ROCKS

Agu ***Biotite granite***—Defined by geophysical expressions of low aeromagnetic signatures in part coincident with gravity lows. Drill core from the western body is composed of pink, medium-grained, variably porphyritic, leucocratic biotite granite that contains phenocrysts of grayish-blue quartz (5 millimeters), perthitic microcline (7 millimeters) with local rapakivi texture, and blocky plagioclase (5 millimeters) in a fine- to medium-grained, aplitic groundmass of quartz and feldspar.

Agn ***Tonalitic to granitic orthogneiss***—Geophysically characterized by irregular aeromagnetic patterns, extended into Morrison County on the basis of mapping to the west in Todd County (Boerboom, 2007).

Avs ***Schistose sedimentary and volcaniclastic rocks***—Defined on the basis of aeromagnetic data and extended into Morrison County on the basis of mapping from surrounding areas (Boerboom, 2007).