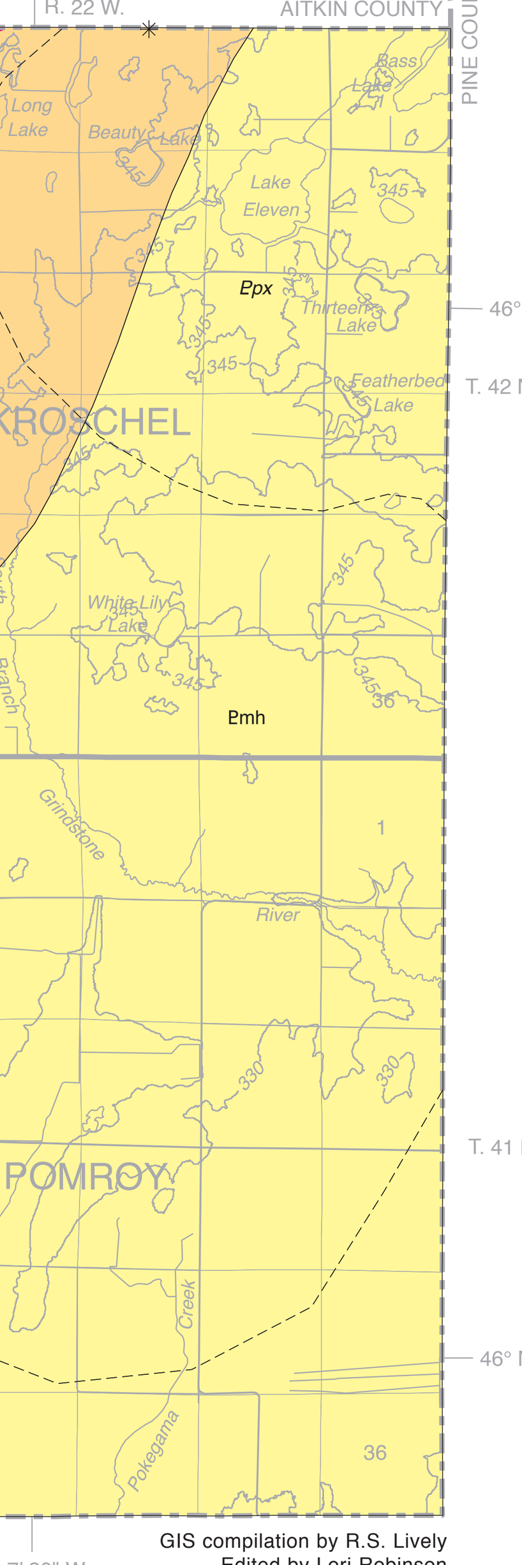
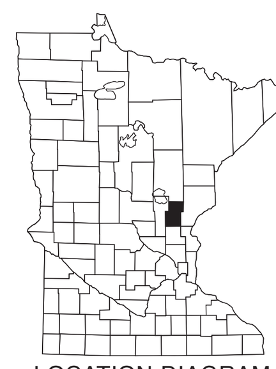


GIS compilation by R.S. Lively
Edited by Lori Robinson



LOCATION DIAGRAM

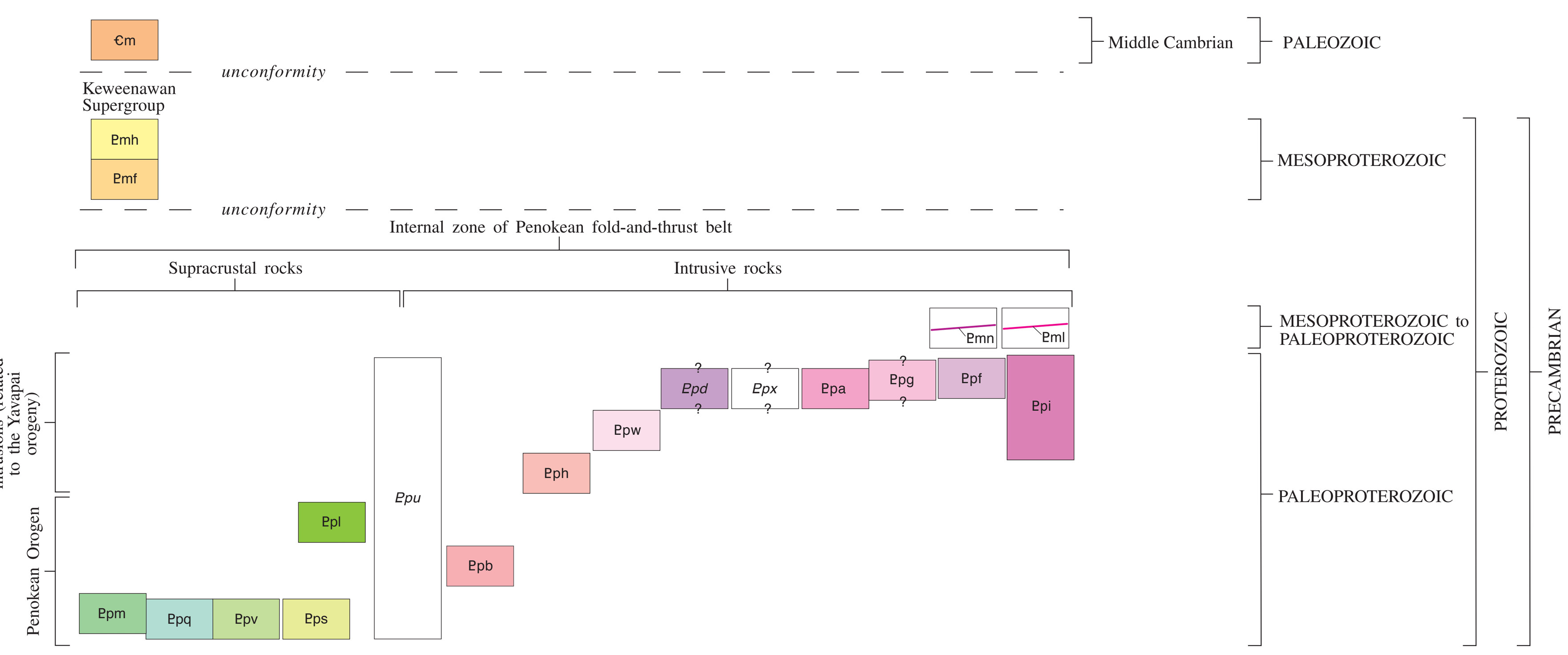
BEDROCK GEOLOGY

By

Terrence J. Boerboom, V.W. Chandler, and Anthony C. Runkel

2016

CORRELATION OF MAP UNITS



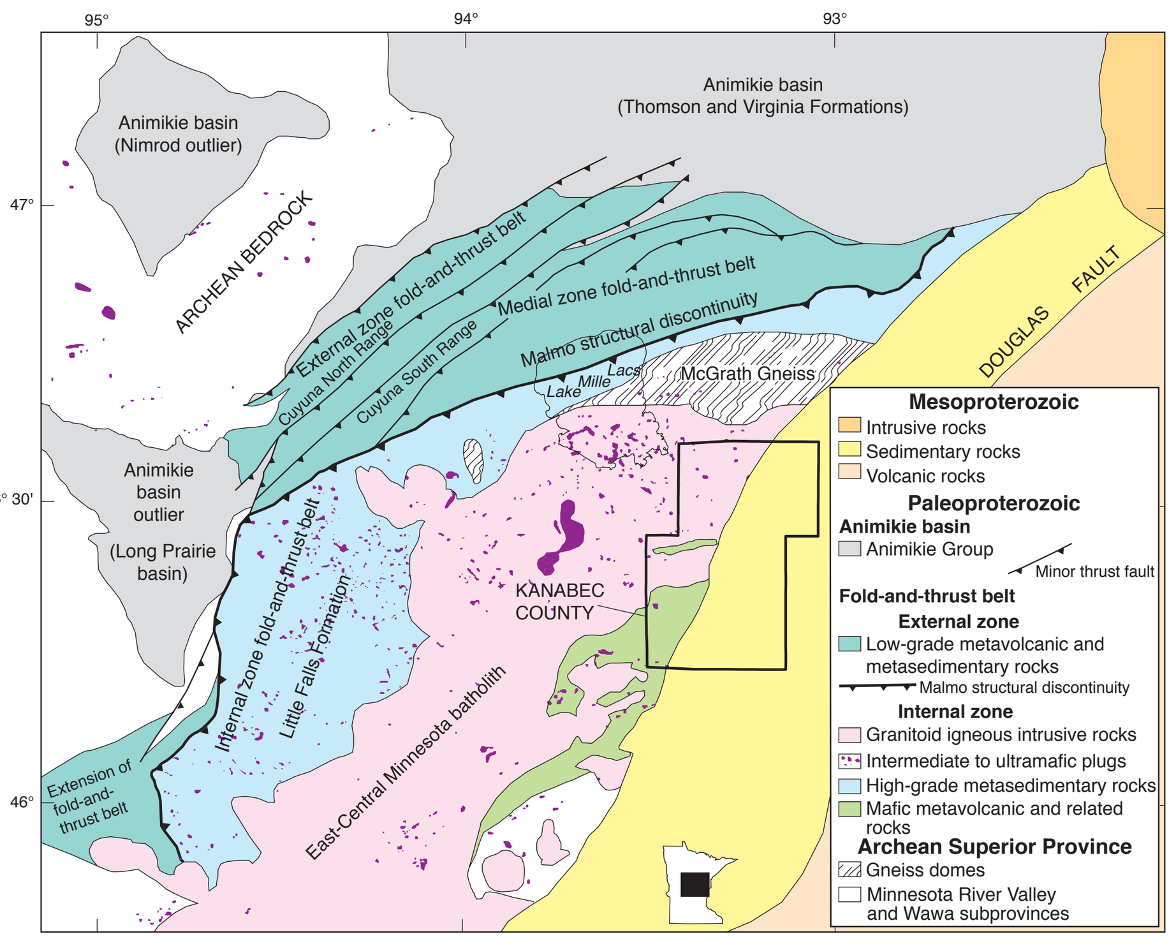


Figure 1. Simplified geologic map of east-central Minnesota showing the major structural elements of Paleoproterozoic rocks of the Penokean orogen and Archean Superior Province. Modified from Jirsa and others (2011).

MAP SYMBOLS

Inferred contact—Mainly located from aeromagnetic data, except where locally controlled by information from drill cores, drilling logs, and bedrock outcrops. Dashed where concealed beneath the Hinckley and Mt. Simon Sandstones and the Fond du Lac Formation.

Weak linear negative aeromagnetic anomaly—Possibly indicative of thin diabase dikes in part, or a reflection of stratigraphic variations in supracrustal rock sequences.

Weak linear positive aeromagnetic anomaly—Possibly indicative of thin diabase dikes in part, or a reflection of stratigraphic variations in supracrustal rock sequences.

Igneous layering and foliation undifferentiated; inclined—Showing strike and dip.

Bedding—Showing strike and dip: inclined. Ball indicates upright topping direction where known.

Minor F_2 fold axis—Showing trend and plunge.

Lineation of metamorphic minerals and concretions—Showing trend and plunge.

Metamorphic foliation—Showing strike and dip: vertical; inclined.

Bedrock outcrop.

Location of bedrock drill hole for which detailed drilling logs and well documented core or cuttings are available.

Location of U-Pb zircon age date sample.

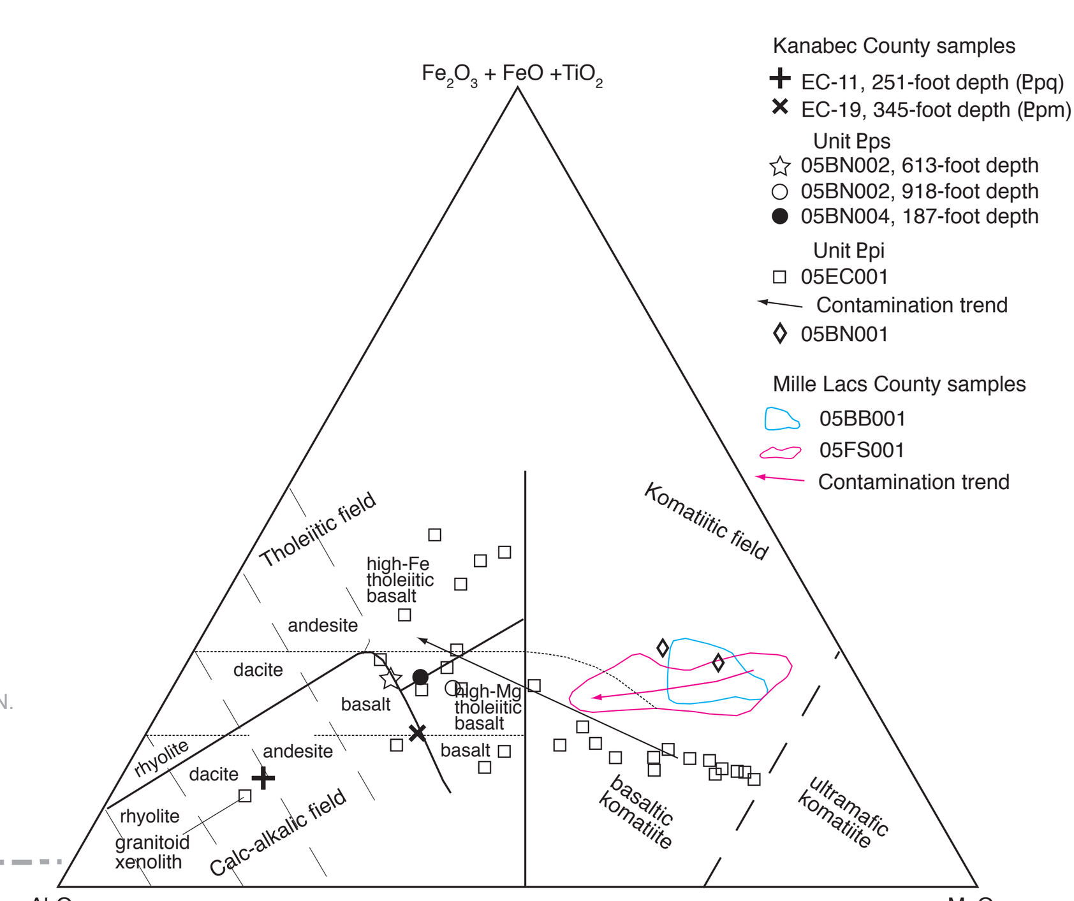
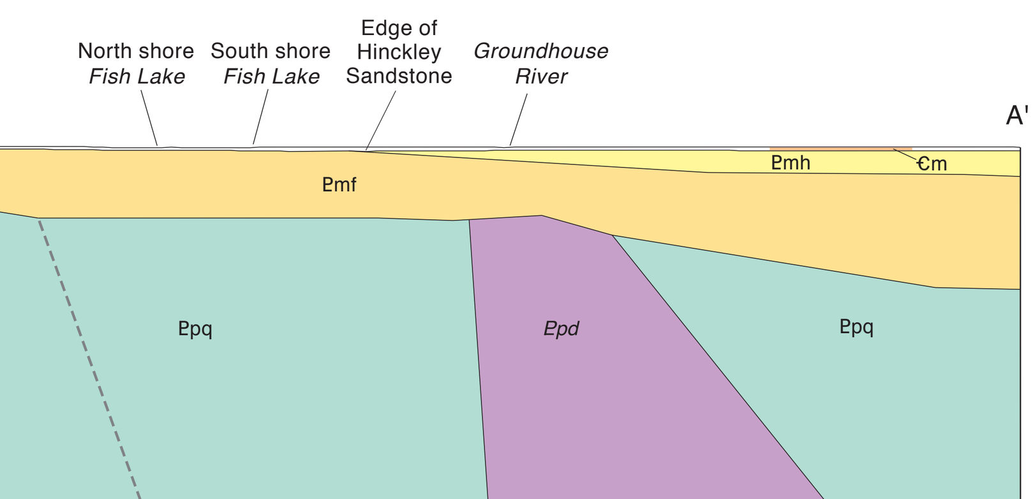


Figure 2. AFTiM diagrams (after Jensen, 1976) for rocks from Kanabec and Mille Lacs Counties, the latter shown for comparative purposes with respect to the mafic and ultramafic intrusive rocks of unit Ᵽpi. The arrows designate the general trend of increasing contamination of primary ultramafic rocks by granitoid and supracrustal country rock xenoliths. The data for samples from drill cores EC-11, 05BN002, and 05BN004 are listed in Table 2. The data for the sample from drill core EC-19 are listed in Appendix C in Jirsa and Chandler (1997). All other data are from mineral exploration company data on file at the Minnesota Department of Natural Resources, Division of Lands and Minerals office in Hibbing.



agnetic data along profiles. The inferred structural grain of subsurface geology is indicated by

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INTRODUCTION

Kanabec County is located near the southern edge of the Canadian Shield and is predominantly underlain by Precambrian bedrock that ranges in age from Paleoproterozoic (approximately 2,200 to 1,780 million years old, or Ma) to Mesoproterozoic (approximately 1,100 Ma; Fig. 1). The Mesoproterozoic rocks are composed of sandstone units that were deposited on the older Paleoproterozoic bedrock types, which continue eastward beneath the sandstones. Scattered outliers of Paleozoic sandstone are also present in the southeastern corner of the county; these unconformably overlie the Precambrian bedrock.

Most of the bedrock is covered by glacial sediment, but the bedrock is exposed at the surface at the north edge of the county in the Snake River valley near its confluence with Hay Creek; at the town of Warman, where there are abandoned quarries; northwest of Mora; and in and near the Ann Lake State Wildlife Management area.

In addition to the bedrock exposed in outcrops, many drill holes to bedrock have been made in the county for purposes of mineral exploration as well as scientific and engineering purposes. Three 185- to 307-foot (56- to 94-meter) deep drill holes in Whited Township (T. 40 N., R. 23 W.), which obtained only cuttings samples, were completed in the 1980s by Rocky Mountain Energy in a conceptual search for uranium deposits, with no positive results. Eight drill cores that range from 217 to 1,095 feet (66 to 334 meters) were obtained in 2005 by Kennecott Exploration in a search for potential base-metal (such as copper and nickel) deposits. Most of these were located in Ann Lake Township (T. 40 N., R. 25 W.), and one was located in Knife Lake Township (T. 40 N., R. 24 W.). Although some of the cores were weakly mineralized, the results were not encouraging enough to prompt any additional drilling. However, these cores provided valuable information about the bedrock geology. Other drill cores obtained by the Minnesota Geological Survey include seven 10-foot (3-meter) long bedrock cores drilled in the 1990s as part of a regional geologic bedrock mapping program, and six short rotary-sonic drill cores obtained as part of this county geologic atlas. The latter were obtained mainly to characterize the glacial sediments that overlie bedrock, but extend several feet into the bedrock. Descriptive logs submitted by water well drillers were also utilized. These logs generally provide only the color and hardness of the rock and hence are of limited value; however, they are useful in delineating the contact between Paleozoic bedrock, Mesoproterozoic sandstone, and Paleoproterozoic crystalline bedrock. See Plate 1, *Data-Base Map*, for details.

These drill cores and cuttings are stored at the core library operated by the Minnesota Department of Natural Resources, Division of Lands and Minerals, in Hibbing. All of the available cores and cuttings were examined for this project and used to help interpret the bedrock geology. 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 Kanabec County was a regional compilation by Southwick and others (1988), and the southwestern corner of the county was included on a regional compilation map by Jirsa and others (2003). Kanabec County was also included in a statewide compilation geologic map (Jirsa and others, 2011).

Three new age dates from Precambrian rock units were obtained as part of this study—two from different phases of the Warman granodiorite (unit Ᵽpw), and one from a metamorphosed gabbro near Mora (unit Ᵽpv). Those ages (using the $^{207}Pb/^{206}Pb$ weighted mean) are reported under the appropriate rock unit descriptions, and their locations are shown on the geologic map (Schmitz, 2014).

GEOLOGIC SETTING AND HISTORY

PALEOZOIC BEDROCK

Paleozoic bedrock is present only in southeastern Kanabec County, where it is interpreted to be erosional remnants and valley fillings of the Mt. Simon Sandstone (unit Ꞓm), at the northernmost extent of the formation. It unconformably overlies the Mesoproterozoic Hinckley Sandstone and Fond du Lac Formation, burying a surface of erosion that had hundreds of feet of relief across southeastern Kanabec and parts of adjacent counties. The isolated erosional remnants shown on this map generally lie between 800 and 900 feet (244 and 274 meters) elevation, whereas the larger area of Mt. Simon Sandstone mapped in the very southeastern corner of the county is part of a more extensive blanket of the formation, contiguous with adjacent parts of Isanti, Chisago, and Pine Counties. In that area, its elevation is likely as low as 700 feet (213 meters), and its maximum thickness is about 150 feet (46 meters).

MESOPROTEROZOIC BEDROCK

The uppermost Precambrian bedrock beneath the eastern half of Kanabec County is composed of thick Mesoproterozoic (about 1,100 Ma) sandstone sequences that are part of the Keweenawan Midcontinent Rift (Mesoproterozoic sedimentary rocks on Fig. 1). The sandstones include the lowermost Fond du Lac Formation, which is made up of red arkosic to lithic sandstone with siltstone and shale interbeds, and the uppermost Hinckley Sandstone, which is composed of tan to yellow quartz arenite. The Fond du Lac Formation, exposed in a few places along the banks of the Snake River near Mora, unconformably overlies older Paleoproterozoic rocks, which can be traced beneath the sandstone by aeromagnetic data. The contact between the Fond du Lac Formation and Hinckley Sandstone is poorly constrained and based almost entirely on the color of the bedrock (for example red vs. yellow) listed on water well logs. The distinction between the Fond du Lac Formation and older Paleoproterozoic rocks to the west is also based on water well log descriptions, but is generally more definitive because the two rock types differ greatly in color and drilling characteristics.

PALEOPROTEROZOIC BEDROCK

Most of Kanabec County is located within the Paleoproterozoic Penokean Orogen, a term that refers to a belt of variably deformed and metamorphosed, predominantly supracrustal rocks that in Minnesota range in age from approximately 2,100 to 1,830 Ma and extend from central Minnesota eastward to Michigan (Southwick and others, 1988). These rocks were deformed and metamorphosed during the Penokean Orogeny at approximately 1,830 Ma, and were also affected by metamorphism at approximately 1,760 Ma due to widespread crustal heating following emplacement of predominantly granitic rocks that range in age from 1,772 to 1,800 Ma (Holm and others, 1998). The latter metamorphic and pluton emplacement ages postdate Penokean orogenesis, and instead overlap the duration of the Yavapai Orogeny, a collisional event focused south of the Penokean Orogen (Schneider and others, 2004; Holm and others, 2007a, b; Van Schmus and others, 2007).

In Minnesota, rocks of the Penokean Orogen are subdivided into two major groups: a 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, less deformed, and only weakly metamorphosed rocks that are collectively termed the Animikie Group (Fig. 1). 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 intrusions and contain several sub-panels dominated by volcanic and sedimentary rocks, including thin iron-formations, which are generally metamorphosed under only greenschist-facies conditions. Rocks of the Penokean Orogen in Kanabec County are contained entirely within the internal zone of the fold-and-thrust belt (Fig. 1) and are dominated by granitic to tonalitic intrusions and poorly constrained mafic to felsic volcanic rock types. For a complete synopsis of the geologic evolution of the fold-and-thrust belt and Animikie basin refer to Southwick and others (1988, 2001), Morey and Southwick (1995), and Schulz and Cannon (2007).

DESCRIPTION OF MAP UNITS

PALEOZOIC ROCKS

Ꞓm **Mt. Simon Sandstone (Middle Cambrian)**—There are neither exposures nor drill hole samples of the Mt. Simon Sandstone from Kanabec County. Based on a single natural gamma log and well driller records in the county, and well samples from adjacent counties, the Mt. Simon Sandstone is dominated by friable, white to tan, medium- to coarse-grained, quartzose sandstone. Interbeds of red and green shale, siltstone, and very fine-grained, feldspathic sandstone are common, particularly in its upper half. Thin beds of quartz-pebble conglomerate occur at several stratigraphic positions, and are especially abundant near the base of the formation. The Mt. Simon Sandstone is distinguished from the Mesoproterozoic Hinckley Sandstone and Fond du Lac Formation on drilling records by being described as generally soft and white, vs. harder, and pink to red or brown.

MESOPROTEROZOIC ROCKS

Ᵽmh **Hinckley Sandstone**—Tan to orange, fine- to medium-grained, well-sorted and well-rounded quartz arenite; composed of about 96 percent quartz (Tryhorn and Ojakangas, 1972), except the lower part contains 10 percent or more of weathered, kaolinitic feldspar. This unit is not exposed at the surface in Kanabec County, but outcrops elsewhere—such as in Pine County to the east—are characterized by trough cross-beds and thin layers of ripple-marked, fine-grained sandstone indicative of deposition in an aqueous environment, and by planar, low-angle cross-beds, possibly indicative of deposition in an eolian environment (Beaster and others, 2000).

Ᵽmf **Fond du Lac Formation**—Pale orange to dusky red, medium- to coarse-grained, arkosic sandstone with interbeds of conglomerate and dark brownish-red siltstone and minor shale. In Kanabec County this unit is exposed in low outcrops along the Snake River just north of Mora, where it is composed of pebble conglomerate with clasts of rhyolite, quartz, and weathered granite. Mooney and others (1970) and Allen (1994) estimated a thickness of as much as 1 to 2 miles (2 to 3 kilometers) for the Fond du Lac Formation adjacent to the Douglas Fault (Fig. 1) based on geophysical data, but in Kanabec County it thins to a feather edge at its western margin.

PALEOPROTEROZOIC TO MESOPROTEROZOIC ROCKS

Diabase and lamprophyre dikes—Scattered normally- and reversely-polarized diabase dikes of unknown width and age are inferred on the basis of very weak and discontinuous, linear positive and negative aeromagnetic lineaments. The positive linear aeromagnetic anomalies are similar in amplitude to ones caused by near-surface phenomena such as buried tunnel valleys within Quaternary glacial deposits, and their depiction here as diabase dikes is speculative.

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

Ᵽml **Woodland lamprophyre dike**—Dark grayish-black, fine-grained, weakly porphyritic lamprophyric dikes that are exposed in outcrops in and near the Snake River upstream from its confluence with Hay Creek. The lamprophyre contains sparse phenocrysts of euhedral pyroxene (salite to ferrosalite) up to 3 millimeters in size in a fine-grained matrix composed dominantly of pyroxene and Fe-Ti oxide minerals in a groundmass of poikilitic alkali feldspar and accessory titaniferous biotite, nepheline, analcime, sphene, apatite, and traces of pyrite, chalcopyrite, calcite, and clots of iddingsite that are likely pseudomorphs of olivine. Compared to normal basalt of similar Mg + Fe content, the lamprophyre is strongly enriched in titanium and phosphorous, as well as incompatible elements (Southwick and others, 2001).

The Woodland lamprophyre, where exposed, is chilled against and intruded into the Warman granodiorite; however, attempts to obtain a U-Pb age date from this dike were unsuccessful. The dike produces a pronounced northeast-trending linear negative aeromagnetic anomaly that is 28 miles (45 kilometers) in length. From where it is exposed it can readily be traced at least 22 miles (35 kilometers) southwest into Mille Lacs County, and 6 miles (10 kilometers) northeast; of this the northeastern-most 3 miles (5 kilometers) are buried beneath the Fond du Lac Formation. In the Snake River valley the dike forks into a northern and southern branch, and to the southwest aeromagnetic data also indicate that the dike forks in places; however, overall the dike is consistently straight along its entire length. Dashed where buried by younger units.

PALEOPROTEROZOIC ROCKS

Ultramafic to intermediate intrusive rocks—More than a dozen small, circular intrusions (unit Ᵽpi) are inferred mainly on the basis of small, high-amplitude, positive aeromagnetic anomalies. Similar aeromagnetic anomalies, which are very abundant to the west and southwest through Mille Lacs, Morrison, and Stearns Counties, have been extensively drilled for both scientific and exploration purposes (for example Boerboom and others, 1995; Boerboom, 2014). These drilling programs have shown that the aeromagnetic anomalies can be interpreted with a high degree of confidence to be caused by small intrusions, particularly where the surrounding bedrock is magnetically featureless, and that the intrusions are composed of intermediate through mafic to ultramafic compositions. In Kanabec County, these aeromagnetic anomalies are confined mostly to the north half of the county and range from 0.03 to 0.2 square miles (19 to 128 acres) in area. Based on geochronologic studies on similar bodies in Morrison County to the west (Keatts and others, 2003; Boerboom, 2014), these intrusions overlap in age with Yavapai-interval granites (such as the Warman and Ann Lake granodiorites in Kanabec County). Age dates on two of these bodies in Morrison County range from 1,791 to 1,770 Ma, ages that are coeval with the main Yavapai-interval granitic plutonism in greater east-central Minnesota. Other intrusions of this suite intrude granites that are as young as 1,774 Ma (Jirsa and others, 2003), indicating that mafic magmatism spanned at least 17 million years.

Also included within this suite of rocks are mafic to ultramafic intrusive bodies that occur within unit Ᵽps, in the central portion of the county. Defining the boundaries of these intrusions within this unit is difficult, because their magnetic signature is masked by the moderate to strong aeromagnetic anomalies of the country rocks which they intruded.

Ᵽpi **Ultramafic to intermediate intrusion, undifferentiated**—Inferred to be composed of ultramafic, mafic, and intermediate-composition intrusions similar to units in Morrison County to the west, for which ample drill core data exist (Boerboom, 2014). Map label is italicized where the unit is buried beneath Mesoproterozoic rocks.

The small unit shown within unit Ᵽps is intersected in three angled drill holes (05EC001, 05EC002, and 05EC003), and is composed of presumed cumulate olivine (now altered to talc and minor tremolite) and clinopyroxene that are surrounded by post-cumulate, Mg-rich, hornblende and phlogopite. Based on the drill cores, this intrusion is inferred to form an irregular dike that is as much as 250 feet (76 meters) thick, which strikes subparallel to the layering in the enclosing supracrustal rocks (unit Ᵽps) and dips steeply to the north. The bottom margin of this intrusion is marked by a rheomorphic intrusive breccia that varies from 80 to 120 feet (24 to 37 meters) in thickness. This magmatic breccia contains numerous angular to partially melted country rock xenoliths composed largely of felsic to intermediate layered gneiss possibly derived from the Hillman tonalite (unit Ᵽph). Coarse-grained appinites characterized by large prismatic hornblende crystals are common near the xenoliths, and are inferred to be a result of contamination by melts derived from partly melted xenoliths. Other drill cores within unit Ᵽps also intersect mafic to ultramafic, variably sheared intrusive rocks, but only in minor proportions and their extent cannot be mapped.

Whole-rock geochemical data of ultramafic rocks from the drill cores in Ann Lake and Knife Lake Townships, obtained from publicly available exploration company data, show two chemically distinct suites of rocks. The mafic intrusion in drill core 05BN001 is chemically indistinguishable from a drill core located in Mille Lacs County to the west (05BB001); both show oceanic crust chemical signatures, with negative potassium, rubidium, strontium, and barium anomalies compared to primitive mantle compositions (Sun and McDonough, 1989). In contrast, analyses of mafic intrusions from drill cores 05EC001, 05EC002, 05EC003, 05BN002, and 05FS001 (core 05FS001 is from Mille Lacs County to the west) show more of an island arc type signature, with pronounced negative tantalum and niobium anomalies. The ultramafic rocks from the drill cores plot within the komatiitic field on a Jensen diagram (Fig. 2; Jensen, 1976). However, many of the analyses from magmatic breccias in drill core 05EC001 grade into the tholeiitic to calc-alkaline basalt fields due to varied degrees of contamination from the surrounding country.

Intermediate to felsic intrusive rocks—Most of northwest Kanabec County is composed of granitic to tonalitic plutons, which collectively form the eastern margin of a larger mass of intrusions known informally as the East-Central Minnesota batholith (Fig. 1). These units are defined by a combination of outcrop and drill core data as well as aeromagnetic and gravity geophysical data.

The oldest unit of the East-Central Minnesota batholith in Kanabec County (unit Ᵽpb) is inferred to be correlative with the 1,877 Ma Penokean Bradbury Creek granodiorite, exposed at the surface in Mille Lacs County to the west, on the basis of similar geophysical properties and age (1,846 Ma in Kanabec County). The rest of the intrusions in Kanabec 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. Intrusions of this age include the Hillman tonalite (unit Ᵽph), the Ann Lake granodiorite (unit Ᵽpa), the Warman granodiorite (unit Ᵽpw), and by inference, granite unit Ᵽpg. The extents of all these intrusions are poorly constrained and they are delineated on the basis of weak geophysical anomaly patterns locally verified by drill cores and outcrops.

Ᵽpf **Granite**—Inferred from a negative gravity signature and corresponding subdued, weak, positive aeromagnetic anomaly to possibly be granite bodies similar to the Foley granite to the west (Jirsa and others, 2003). Map label is italicized where the units are buried beneath Mesoproterozoic rocks.

Ᵽpw **Warman granodiorite to tonalite**—Pink on weathered surfaces, gray on fresh break, medium-grained, variably foliated biotite granodiorite to trondhjemitic tonalite cut by late-phase pink muscovite pegmatite granite dikes and pods. This unit contains multiple phases that range from strongly- to weakly-foliated biotite tonalite to muscovite-bearing biotite granodiorite, but these are difficult to differentiate on the weathered outcrop surfaces, and discrimination requires detailed mapping beyond the scope of this study. Zircons obtained from a sample near Warman yielded an age 1,787 ± 3 Ma (Holm and others, 2005). Recently obtained U-Pb zircon ages (Schmitz, 2014) from the outcrops near the north edge of the county in the Snake River valley show that the biotite tonalite phase (1792.6 ± 0.5 Ma; sample KB001) overlaps the biotite granodiorite phase (1,793.3 ± 0.7 Ma; sample KB021). Petrographic examination of samples revealed that most rocks identified as muscovite-bearing biotite granite in hand sample are actually granodiorite to "plagiogranite" (trondhjemite). Inclusions of biotite schist (unit Ᵽpl) are common in the outcrop exposures. Granodiorite phases commonly contain poikilitic microcline. The extent of this unit is defined by a broad, featureless aeromagnetic anomaly signature that extends west into Mille Lacs County (Boerboom and others, 1999). Map label is italicized where the unit is buried beneath Mesoproterozoic rocks.

Ᵽpg **Granite, undifferentiated**—Lithology and extent are inferred entirely from geophysical data. Unit is possibly the eastern extension of the 1,779 ± 4 Ma (Holm and others, 2005) Foley granite (Jirsa and others, 2003), but unlike the Foley granite, which is typically associated with low gravity signatures, this area is marked by a moderate positive Bouguer gravity anomaly.

Ᵽpa **Ann Lake granodiorite**—Pale salmon color on weathered surfaces, gray on fresh break, medium- to coarse-grained, weakly foliated sphene- and muscovite-bearing biotite-hornblende granodiorite that locally contains poikilitic microcline. Shown as granite on previously published maps (Jirsa and others, 2003), but further petrographic examination for this study shows it to be primarily granodiorite. Geophysically characterized by a pronounced positive aeromagnetic anomaly and corresponding low Bouguer gravity anomaly. Based on aeromagnetic data, this pluton continues 5 miles (8 kilometers) east beneath the Fond du Lac Formation, and the overall pluton size is approximately 14 by 5.5 miles (23 by 9 kilometers). The pluton is bisected by a prominent aeromagnetic low that is interpreted to be a possible right-lateral fault subsequently intruded by granite of unit *Ᵽpu*. A sample of the Ann Lake granodiorite yielded a U/Pb zircon age of 1,784 ± 10 Ma (Holm and others, 2005).

Ᵽpd **Granodiorite buried beneath Mesoproterozoic sedimentary rock**—Inferred from moderate corresponding positive gravity and aeromagnetic anomalies to be an intermediate intrusive body such as granodiorite (Jirsa and others, 2003).

Ᵽph **Hillman tonalite**—Unit extent is inferred from a very weak positive aeromagnetic pattern. This unit is well-mapped to the west in Morrison County (Boerboom, 2014), but its extension to the east is highly speculative; alternatively, the bedrock in this area could be composed of the Warman granodiorite. Samples of the Hillman tonalite from three separate localities in Morrison County yielded ages from 1,792 to 1,800 Ma, with a mean age of 1,795 Ma, and a composite regression age for the three samples of 1,797 ± 4 Ma (Holm and others, 2005).

Ᵽpb **Bradbury Creek granodiorite**—Pinkish-red and black mottled, coarse-grained, weakly-foliated, sphene-bearing biotite granodiorite verging on tonalite. The extent is defined by a moderate-amplitude positive aeromagnetic anomaly pattern and the lithology is based on a single 10-foot (3-meter) long drill core (EC-8; Jirsa and Chandler, 1997). A sample from the drill core gave an Ar/Ar age of 1,846 ± 6 Ma (Holm and others, 2005), which places a minimum constraint on the age of emplacement. Although this age likely reflects regional metamorphism during the late stages of the Penokean Orogeny, it is consistent with the 1,858 to 1,877 Ma U-Pb zircon dates obtained from outcrop samples at the type locality near Bradbury Creek in Mille Lacs County to the west.

Ᵽpx **Granitoid intrusion buried beneath Mesoproterozoic sedimentary rock**—Characterized by a negative gravity and aeromagnetic anomaly pattern.

Ᵽpu **Granitoid to supracrustal rock buried beneath Mesoproterozoic sedimentary rock**—Characterized by a slightly positive gravity anomaly pattern and a subdued low aeromagnetic anomaly pattern; detailed composition is unknown.

Metamorphic rocks—The nomenclature 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, and so on. In instances where the metamorphic grade is high enough to have caused substantial recrystallization the terms *schist* or *gneiss* may be used, with mineralogic modifiers such as garnet, biotite, or staurolite.

Schistose metamorphic rocks within the internal zone of the Penokean Orogen (Southwick and others, 1988) in Kanabec County (Fig. 1) are poorly exposed and their distribution and lithology are inferred primarily from scattered drill core information coupled with geophysical data. Rocks in this group include a narrow east–west belt in the central part of the county (unit Ᵽps) that apparently forms a remnant screen of supracrustal country rocks located between later granitoid intrusions; this belt also includes mafic to ultramafic intrusions largely emplaced subsequent to metamorphism and deformation (see unit Ᵽpi). The bedrock in the southern portion of Kanabec County is likewise thought to be composed of metamorphosed supracrustal rocks of volcanic and sedimentary protolith, as well as deformed mafic-intermediate intrusive rocks.

Ᵽpl **Muscovite-biotite schist of metasedimentary protolith**—Gray, strongly foliated mica schist (metamorphosed graywacke and argillite) that locally contains garnet, staurolite, and sillimanite. Occurs as xenoliths of varied size within the Warman granodiorite (unit Ᵽpw). Locally contains lineated, metamorphosed calcareous concretions composed of garnet, epidote, hornblende, and plagioclase, and black tourmaline is present locally in small zones adjacent to the Warman granodiorite in the north-central part of the map along the Snake River. Despite the fact this unit clearly forms xenoliths within the Warman granodiorite, the dominant metamorphic foliation consistently strikes east–west and dips 30° to 70° south, and lineated metaconcretions predominantly plunge shallowly to the east in the plane of foliation. Upright, south-younging graded beds were observed locally. The consistency of foliations and lineations between different outcrop areas, inferred to represent separate xenoliths within the enclosing granitoid rocks, implies that the original orientations of bedding and metamorphic foliations were close to their present positions. This schist is correlated with the Little Falls Formation (for example Boerboom, 2014) on the basis of similar composition, bedding style, metamorphic grade, and concretions, and may represent a roof pendant within the Warman granodiorite. In places the schist occurs as small xenoliths within an early, strongly foliated tonalite possibly analogous to the Hillman tonalite, which is in turn included within the Warman granodiorite.

Ᵽps **Interlayered metamorphosed sedimentary and mafic volcanic rock**—A mixed sequence of largely supracrustal (sedimentary and volcanic) rock types dominated by metamorphosed graywacke/argillite (mica schist) and mafic volcanic rocks (amphibolite), with lesser proportions of graphitic argillite, chert, and dolomitic marble. Also includes small mafic to ultramafic intrusions that are not mappable at this scale (see unit Ᵽpi). All except the mafic intrusions are regionally metamorphosed to the amphibolite facies, and possibly also thermally metamorphosed by the mafic intrusions within the unit as well as the surrounding granitoid batholiths. This unit was drilled extensively (eight drill cores totaling over 6,000 feet [1,829 meters]) within the past decade in a search for potential base metal (copper, nickel) deposits.

The composite average of the over 6,000 feet of drill core obtained from this map unit is approximately 42 percent graywacke/argillite, 26 percent ultramafic to mafic intrusive igneous rocks, 13 percent sedimentary rocks with mafic tuffaceous component, 13 percent massive basalt, 2 percent each of fragmental mafic volcanic rocks, chert, and carbonate, and minor proportions of intrusive breccia and small granitoid intrusions. About 26 percent of the graywacke/argillite portion is graphitic to varied degrees, and about 14 percent contains thin carbonate interbeds (Table 1).

Primary graywacke/argillite beds are metamorphosed to mica-quartz-plagioclase schist, with varied amounts of garnet and rare sillimanite, staurolite, clinopyroxene, and possible cordierite; local thin beds of brown dravite tourmaline were noted in some tuffaceous layers. Garnets exhibit snowball textures, and are variably retrograded to chlorite. Some sulfide-rich intervals are composed of albitite, possibly indicative of sodic alteration prior to metamorphism, and variable proportions of strongly magnetic pyrrhotite are present, locally forming semi-massive sulfide intervals.

Green mafic volcanic rocks vary from massive, to locally weakly pillowed, to fragmental, with minor subvolcanic metagabbroic sills or coarse flow interiors. The massive flow units are weakly and variably amygdaloidal and are now recrystallized to amphibole-plagioclase schist. Fragmental portions contain irregular centimeter- to decimeter-sized fragments of dark green amphibolite in a light green plagioclase-amphibole matrix, with lesser proportions of epidote, clinopyroxene, and titanite. Major-element geochemical analyses of two samples of massive metabasalt (Table 2, samples KBN2[2] and KBN4) plot as high Mg tholeiitic basalt on a standard Jensen cation plot (Fig. 2; Jensen, 1976).

A substantial proportion of the cores are composed of ambiguous schists containing 50 percent or more biotite as centimeter-thick layers that alternate with amphibole-rich layers, interpreted to be a primary sedimentary rock with a large mafic tuff component. This unit locally contains substantial clinopyroxene (salite to ferrosalite). The major-element geochemical composition of one sample (Table 2, sample KBN2[1]) plots near the two massive basalt samples but slightly into the calc-alkaline basalt field on the Jensen cation plot. This could be interpreted to be dilution by siliciclastic sedimentation concurrent with mafic tuff input. However, the K_2O value of this rock is over eight times that of the massive basalt samples, possibly an indication that the rock has undergone potassic alteration prior to metamorphism.

Dolomitic marble occurs as 3- to 10-foot (1- to 3-meter) thick layers interpreted to be primary beds of muddy carbonate. They now contain assemblages dominated by granoblastic to rhombic dolomite and interstitial calcite along with varied proportions of diopsidic clinopyroxene, muscovite, biotite, chlorite, pyrrhotite, ilmenite, pyrite, sphene, actinolite, tremolite, talc, minor fuchsite, and minor veinlets of adularia.

Cherty intervals are generally thin, with the exception of drill core 05RH001, in which the upper 80 feet (24 meters) of the core is chert that overlies 4 feet (1 meter) of carbonate, which in turn grades downward into graywacke/argillite.

Based on reversals in younging directions in graywacke units, these supracrustal rocks may have been folded by an early deformation event prior to the main fabric-forming metamorphic event. Both bedding and foliation are assumed to strike roughly east–west, parallel to the moderate positive aeromagnetic anomaly. The dip directions cannot be confidently gleaned from the drill core, but the best estimate is that the sequence dips variably from 35° to 70° north.

Ᵽpv **Mafic volcanic to intrusive rock and siliceous schist**—A poorly understood unit characterized by discontinuous east–northeast-trending, linear positive aeromagnetic anomalies of low amplitude that may represent layering or stratification, and a corresponding strong, positive Bouguer gravity anomaly. Alternatively the linear aeromagnetic anomalies could be discontinuous dikes related to unit Ᵽmn. Near the west end of this unit one short drill core (EC-9) intersected a dark greenish-gray, strongly shear-foliated amphibole-quartz-feldspar schist of intrusive igneous protolith, which contains augen-like lenses of recrystallized quartz and plagioclase, and strung-out clusters of small blocky opaque oxide minerals that may have been coarse-grained oxides prior to shearing. In local, less deformed zones the quartz and feldspar exhibit relict myrmekitic texture, which indicates the protolith may have been a relatively coarse-grained, intermediate-composition intrusive rock such as diorite.

Along the north margin of this unit a short drill core (KR-1) intersected fine-grained carbonate-sericite-quartz schist with layers of semi-massive to massive pyrite, interpreted to be either an exhalite or a highly-altered felsic volcanic as indicated by ovoid clots of sericite and carbonate that are possibly pseudomorphs of early feldspar phenocrysts.

Farthest east in this unit, northwest of Mora, are several outcrops of moderately to strongly foliated, amphibolitic metagabbro that exhibits a relict coarse-grained, porphyritic texture, now composed of varied proportions of actinolite and possibly tremolite; chlorite, epidote, sphene, leucoxene, and traces of biotite, calcite, and opaque oxides and sulfides. Plagioclase is highly saussuritized and clinozoisite-altered. These outcrops apparently form a topographic knob that is surrounded by sandstone of the Fond du Lac Formation, based on descriptive water well logs in the surrounding area; however, it is apparent from geophysical data that it is part of the same body as west of the sandstone. Zircons from a sample (KB034B) from these outcrops yielded a U/Pb zircon age of 1,880.3 ± 0.6 Ma (Schmitz, 2014).

Ᵽpm **Mafic to intermediate intrusive to volcanic rock**—This unit is delineated on the basis of irregular, linear, east–northeast trending, positive aeromagnetic anomalies of moderate to high amplitude that continue as far as 10 miles (16 kilometers) west–southwest into Mille Lacs County, where they are truncated by the Foley granite pluton.

The lithology is based on a single 10-foot (3-meter) drill core (EC-19), which is composed of dark gray, fine- to medium-grained, massive, deuterically altered and sparsely amygdaloidal quartz monzodiorite to diorite. Despite extensive deuteric alteration the primary texture is well preserved, and there is no indication of a tectonic-metamorphic overprint. The rock contains strongly zoned, altered plagioclase crystals up to 1 millimeter in size that are rimmed by micrographic quartz-alkali feldspar, and interstitial masses of biotite mixed with other Fe-silicate minerals, fibrous actinolitic amphiboles, minor prismatic hornblende, accessory pyrite, apatite, Fe-Ti oxides, and secondary chlorite and leucoxene. This assemblage is probably in part alteration products of primary magmatic poikilitic hornblende or pyroxene. Small amygdules visible on the core surface are filled with calcite and prismatic amphiboles, with cores of quartz in the larger amygdules; other cavities are filled with chlorite. Minor late brittle veins are filled with calcite and what is tentatively identified as prehnite.

A minor proportion of this short drill core is composed of a magmatically related, dark green, fine-grained rock that contains abundant brown prismatic hornblende, substantial interstitial quartz, and is in sharp contact with the more coarse-grained phase. A single geochemical analysis (Jirsa and Chandler, 1997) of this phase plots as calc-alkaline basalt on a standard Jensen classification plot (Fig. 2; Jensen, 1976).

The pristine igneous texture of this rock contrasts sharply with other rock types intersected in drill core or exposed in outcrops within this belt, which all contain a strong metamorphic fabric. It may be similar, in terms of general mineralogy, deuteric alteration, and lack of tectonic foliation, to mafic phases of the Watab diorite (Jirsa and others, 2003), which lies along the trend of the aeromagnetic anomalies to the west, but on the west side of the intervening Foley granite pluton. Alternatively, these anomalies may be caused by mafic metavolcanic rocks interlayered with felsic to intermediate-composition schists of volcano-sedimentary protolith (unit Ᵽpf), in which case the drill hole may have intersected a narrow, intrusive dike not representative of the aeromagnetic anomalies.

Ᵽpq **Schistose porphyritic felsic volcanic rock**—Orange-gray, fine- to medium-grained, porphyritic, fragmental to massive lapilli tuff and possible lava flow with a superimposed metamorphic foliation that dips approximately 70° from horizontal. The phenocrysts are composed of quartz (1 to 2 percent, up to 3 millimeters in diameter) and plagioclase (3 to 4 percent, up to 3.5 millimeters in size), set in a matrix of finely granoblastic quartz and feldspar intergrown with tiny, strongly foliated prismatic amphibole (15 percent). In more massive parts of cores, where the rock is interpreted to be a possible flow, the quartz phenocrysts show euhedral crystal faces, embayments, and sharp extinction, all characteristics of volcanic phenocrysts. Plagioclase crystals are fresh and blocky in shape, indicating that they are also phenocrysts. Other intervals of the cores contain lighter-colored, 1- to 7-centimeter long, elliptical lenses of porphyritic felsite interpreted to be possible lapilli fragments surrounded by darker-colored, more strongly foliated matrix material. These cores were previously interpreted to be highly sheared granitic intrusive rocks, but the characteristic phenocryst morphologies indicate this unit is most likely a porphyritic, fragmental to massive felsic volcanic rock. The extent is speculative and based on aeromagnetic lows that partly correspond to Bouguer gravity lows, and the lithology is based on two drill cores (EC-11 and EC-20). Major-element geochemical data (Table 2, sample EC-11) from one sample of this rock plot as calc-alkaline dacite on a Jensen cation plot (Fig. 2; Jensen, 1976).

This unit may include an unknown proportion of highly sheared and cataclasized granitoid rocks near the south edge of the county as indicated by a drill core located just south of the county border in Isanti County; however, there is no evidence in the geophysical anomaly data to indicate that this granite forms a mappable unit within Kanabec County.