UNIVERSITY OF MINNESOTA
MINNESOTA GEOLOGICAL SURVEY
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Prepared and Published with the Support of
THE CARLTON COUNTY BOARD OF COMMISSIONERS,
THE MINNESOTA DEPARTMENT OF NATURAL RESOURCES, DIVISION OF WATERS, AND
THE FOND DU LAC BAND OF LAKE SUPERIOR CHIPPEWA

COUNTY ATLAS SERIES
ATLAS C-19, PART A
Plate 6—Mineral Endowment

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

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

SCALE 1:200 000
5 0 5 10 MILES
5 0 5 10 15 KILOMETERS

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

DESCRIPTION OF MAP UNITS

Plate 2, *Bedrock Geology*, contains a complete description of map units.

MESOPROTEROZOIC

- Emh — Hinckley Sandstone.
- Emf — Fond du Lac Formation.
- Emc — Basalt, Chengwatana Group.
- Emi — Interflow sandstone, Chengwatana Group.
- Edc — Cloquet dike.
- Eme — Esko oxide gabbro.
- Emt — Tamarack intrusion.

PALEOPROTEROZOIC

Thomson Formation

- Eto — Slate and graywacke.
- Eth — Hornfels of slate and graywacke protolith.
- Ett — Variably graphitic slate and graywacke.
- Etg — Graphitic slate and graywacke.
- Etm — Sulfidic-graphitic slate, metagraywacke, minor chert (includes units Epg and Epc).

Mille Lacs Group

- Egs — Graphitic schist, silicate-facies iron-formation, chert, and metagabbro.
- Emg — Dominantly mafic volcanic and hypabyssal intrusive rocks.
- Ecs — Carbonaceous argillite and iron-formation.
- Evg — Dominantly mafic volcanic and hypabyssal intrusive rocks, lesser metasedimentary rocks.
- Eca — Carbonaceous argillite.
- Ega — Mixed mafic rocks and sedimentary rocks.
- Eag — Graphitic schist and metagraywacke.
- Eg — Metagabbro.
- Emm — Dolomitic marble.

Little Falls Formation

- Egg — Metagraywacke.

MAP SYMBOLS

- Geologic contact
- Strike-slip fault—Speculative
- Thrust fault—Inferred
- Malmo structural discontinuity
- Electromagnetic anomaly
- Bedrock outcrop

Location of a drill hole targeting:

- Scientific research
- Base and precious metals
- Methane
- Uranium
- Sulfur

Exploration area discussed in the text

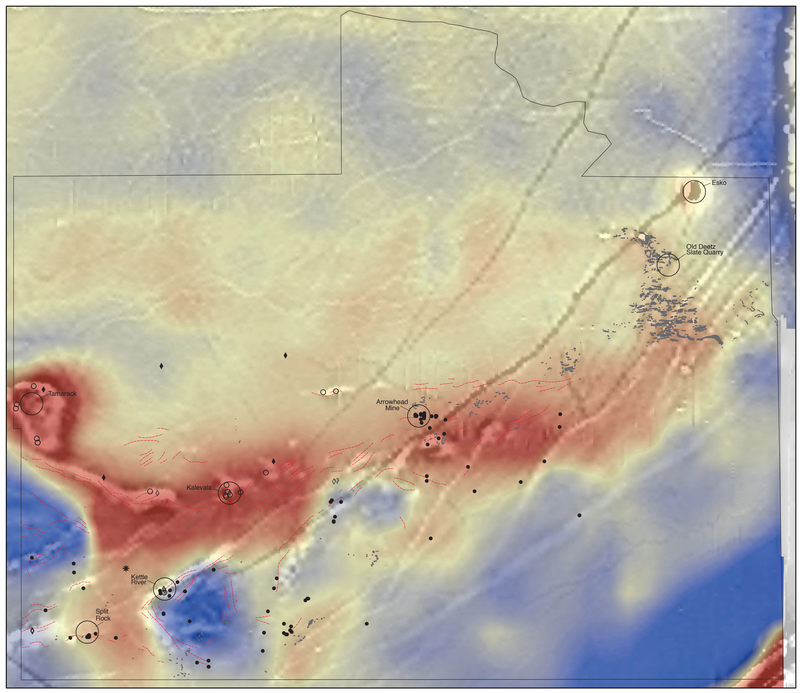

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Figure 1. First-vertical derivative aeromagnetic data superimposed on second-vertical derivative Bouguer gravity data. Aeromagnetic data (shaded in grayscale) show relative magnetic susceptibility of bedrock: lighter shades are more magnetic, grayer shades are less magnetic. Gravity data show relative density of bedrock: red shades are created by more dense rocks such as basalt, mafic intrusions, and iron-rich metasedimentary rocks; blue areas are created by less dense rocks such as metagraywacke and sandstone.

Table 1. History of exploratory and scientific drilling in Carlton County

Company	Year	Number of holes	Footage sampled	Commodity	Samples stored at
U.S. Bureau of Mines	1951, 1954	5	1,383	Sulfur, base metals, iron?	MNDNR, Hibbing Core Repository
Hanna Mining	1952	7	612	Sulfur, base metals, iron?	MNDNR, Hibbing Core Repository
Unknown (EL-1, 2)	1950s?	2	225	Base metals (?)	Minnesota Geological Survey
Turmoil, Inc.	1978	1	6,637	Methane gas	Minnesota Geological Survey
Rocky Mountain Energy	1977-1980	33	13,639	Uranium	MNDNR, Hibbing Core Repository
Energy Reserve Group	1978-1980	12	4,759	Uranium	MNDNR, Hibbing Core Repository
Urangesellschaft	1979	2	250	Uranium	MNDNR, Hibbing Core Repository
Martin-Trost	1979-1980	16	3,956	Uranium	MNDNR, Hibbing Core Repository
Anaconda	1980	7	2,702	Uranium (?)	MNDNR, Hibbing Core Repository
RUSC Inc.	1986	9	2,470	Uranium (?)	MNDNR, Hibbing Core Repository
Great Lakes Exploration	1988-1993	7	1,502	Base metals	MNDNR, Hibbing Core Repository
Cominco	1995-1998	6	2,457	Base metals	MNDNR, Hibbing Core Repository
Kennecott Minerals	2004-2008	7	8,226	Base and precious metals	Kennecott Offices
Minnesota Department of Transportation	1960-1971	17	200	Road construction	MNDNR, Hibbing Core Repository; Minnesota Geological Survey
Minnesota Geological Survey	1984	5	47	Regional geologic interpretation	MNDNR, Hibbing Core Repository
MNDNR	1984-1985	2	4,743	Base metals	MNDNR, Hibbing Core Repository
TOTAL		138	53,808		

MNDNR: Minnesota Department of Natural Resources

Base metals include copper, zinc, nickel, lead, and iron. Precious metals include gold, platinum group elements, and silver.

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Every reasonable effort has been made to ensure the accuracy of the factual data on which this map interpretation is based; however, the Minnesota Geological Survey does not warrant or guarantee that there are no errors. Users may wish to verify critical information; sources include both the references listed here and information on file at the offices of the Minnesota Geological Survey in St. Paul. In addition, effort has been made to ensure that the interpretation conforms to sound geologic and cartographic principles. No claim is made that the interpretation shown is rigorously correct, however, and it should not be used to guide engineering-scale decisions without site-specific verification.

MINERAL ENDOWMENT

By

Terrence J. Boerboom

2009

INTRODUCTION

The terms *mineral* or *geologic endowment* and *mineral resource* refer to geologic materials that have intrinsic economic value and thus potentially could be mined and marketed. Some examples of these materials are gold, copper, nickel, iron, uranium, platinum-group elements, crushed rock aggregate, sand and gravel aggregate, and building stone. The *geologic endowment* of a mineral commodity can be defined and quantified on observable physical and compositional attributes of the deposit, such as deposit thickness and horizontal dimensions, grade and tonnage, overburden thickness, measure of crushing strength, and particle-size distribution. A *mineral resource* is a narrower subset of a mineral endowment; it is an occurrence of geologic material of economic interest in such form and quantity that reasonable prospects for eventual economic extraction exist. If a part of the deposit does not have reasonable prospects for eventual economic extraction, it cannot be included in a mineral resource (Resources and Reserves Committee, 1999). Factors that may remove some portion of an endowment from consideration as a resource are zoning restrictions, land ownership considerations, prohibitive taxation, competing surface uses, and environmental considerations, in addition to the supply–demand–price fluctuations of the commodity marketplace. Therefore a mineral resource must possess favorable geologic attributes and also be relatively unencumbered by socioeconomic factors that would remove it from consideration as the basis of a business enterprise. The author of this plate did not take into account these socioeconomic factors, and therefore the map portrays the mineral endowment, not the mineral resources of Carlton County.

This plate addresses the geologic endowment of only the bedrock beneath Carlton County. It does not address surficial materials such as sand and gravel aggregate resources, nor does it fully address the bedrock materials that might be suitable for use as crushed stone or building stone. Part B of the Carlton County Geologic Atlas, to be produced by the Minnesota Department of Natural Resources, will provide maps that portray the size and quality of sand and gravel deposits, as well as more details on potential bedrock sources for industrial minerals such as crushed stone.

The bedrock endowment map is a derivation of the bedrock geologic map (Plate 2, *Bedrock Geology*). On this plate, map units Eto, Ega, and Egg, composed of slate and graywacke (and their metamorphic equivalents), are not colored; these areas are least likely to be explored for mineral occurrences, given our current understanding of the bedrock geology and known types and models of mineral deposits. Likewise, map units Emc, Emi, Emf, and Emh (Keweenawan sedimentary and volcanic rocks) are not colored for the same reason. In the future, more detailed information about the bedrock geology may be learned and new models of mineral exploration may be developed that could lead to exploration in these areas as well. Also, many of the rocks in those units not colored on the map may prove to be suitable for use as industrial minerals such as crushed stone or paving stone, but those commodities are not the focus of this map. The colored map units shown on the bedrock endowment map are dominated by rock types such as pyrite and/or pyrrhotite-rich sedimentary rocks, mafic intrusions, and mafic volcanic rocks, which are most likely to host metallic mineral deposits based on analogy with known mineral deposits elsewhere. Several of these areas have already been explored to varying degrees, and will likely be the focus of future mineral exploration endeavors. Figure 1 shows the first-vertical derivative aeromagnetic data superimposed on second-vertical derivative Bouguer gravity data, with the locations of drill holes, outcrops, and electromagnetic anomalies indicated. In areas such as Carlton County, which are covered by glacial sediments, these are the kinds of data likely to be used for minerals exploration.

Compared to many areas of east-central Minnesota, the bedrock in parts of Carlton County is relatively well exposed, but nonetheless, only a tiny fraction of the bedrock is visible at the land surface. However, the bedrock exposures, when coupled with geophysical data such as aeromagnetic maps and airborne and ground electromagnetic surveys, can provide clues to help guide exploratory drilling efforts.

This plate is intended to be used largely as a guide for county land managers and land owners to understand which areas may be explored for minerals in the future. It does not provide specific information such as metal assay values or regional geochemical studies. For specific information the reader is referred to files stored at the office of the Minnesota Department of Natural Resources, Division of Lands and Minerals, in Hibbing, Minnesota. Carlton County is also included in a report on the sedimentary-exhalative zinc potential of a larger area of east-central Minnesota, in which some specific assay values for zinc and other metals are reported (Severson and others, 2003).

DRILLING HISTORY

Carlton County has been extensively searched for various types of mineral deposits, mainly uranium and base metals such as copper, zinc, and lead. Electromagnetic and gravity data collected by companies as part of those exploration efforts were made available to the Minnesota Geological Survey and were compiled on a regional geologic map that includes part of Carlton County (McSwiggen, 1987). The electromagnetic anomalies shown on this map are taken from that compilation. Exploratory drilling by mineral exploration companies, and to a lesser degree by governmental agencies, has been ongoing at various rates since at least the early 1950s. At the time this map was constructed, approximately 138 exploratory drill holes were drilled in the county (Table 1). Many small prospect pits and purported silver mines are reported throughout the southwestern portion of the county, but it has never been verified that any metals were actually extracted.

Known exploratory drilling in Carlton County began in the 1950s, when the U.S. Bureau of Mines and Hanna Mining Company targeted some aeromagnetic anomalies for prospective pyrite-pyrrhotite bodies similar to those in the Glen Township area in Aitkin County to the west (Table 1; Pennington and Davis, 1953). Most of the exploratory drilling in Carlton County occurred during a cycle of uranium exploration in the 1980s by several companies. Since that time to the present, mineral exploration activity, mainly for base metals such as zinc, has proceeded slowly. The total sampled footage, as surmised mainly from records at the Minnesota Department of Natural Resources, Division of Lands and Minerals as well as information at the Minnesota Geological Survey, is nearly 54,000 feet (16,459 meters), of which approximately 14,000 feet (4,267 meters) is in the form of rock cuttings rather than drill core. It is likely that mineral exploration activities in Carlton County will continue for base metals such as zinc, copper, lead, nickel, platinum-group elements, and possibly titanium and vanadium. Not included in Table 1 are second-hand reports of drilling on the Esko oxide gabbro, for which no cores or drilling records are available.

CRUSHED ROCK AGGREGATE, ROOFING SLATE, PAVING STONE, AND BUILDING STONE

Most of the bedrock in Carlton County that is exposed at the surface or only shallowly buried by glacial sediment is composed of metamorphosed sedimentary and volcanic rock types such as slate, phyllite, schist, and greenstone (metamorphosed mafic volcanic and intrusive igneous rocks). In regard to aggregate use, the metasedimentary rocks tend to have substandard strength and shape properties, and if weathered, possess absorptive capabilities that make them undesirable for use in concrete or asphalt road construction and bridge superstructures. Other types of bedrock, such as Paleoproterozoic greenstone and siliceous graywacke (with low mica content), and Mesoproterozoic basalt and diabase, may meet some quality requirements for those structures. Also, lower quality aggregate that does not meet highway construction standards may still be suitable for use in maintaining township gravel roads.

Slate beds in the Thomson Formation have been quarried in the past for roofing tiles, for example at the site of the *Old Deetz slate quarry* between Cloquet and Esko. According to the Minnesota Office of Tourism, this quarry was active from 1854 to 1911, was mined to a depth of 100 feet (30 meters) with tunnels, and the slate was reportedly used in local building projects. In addition, limited quarrying for stone pavers and building facing has taken place in Pine County, just south of the Carlton County border, and similar rock types are found in southern Carlton County, where the bedrock typically contains a strong schistose habit, and consequently naturally breaks into flat slabs that could be exploited as paving stone.

An unknown but probably small quantity of sandstone from the Fond du Lac Formation was extracted in the late 1800s from two small quarries just east of the map area near the St. Louis River (Bowles, 1918). Although these quarries have long been inactive, there is currently a small demand for brown sandstone similar to this, mainly for building restoration and repair.

Large quantities of Hinckley Sandstone were quarried in the late 1800s to early 1900s along the Kettle River in Pine County, south of Carlton County. All of the historically quarried areas are now located within Banning State Park, which precludes them from being reopened. However, there is a small demand for this light-colored sandstone as material for building restoration projects. Although there are few known outcrops of the Hinckley Sandstone in Carlton County, the rock is likely close to the surface in many areas, and it may be evaluated as a possible resource.

Part B of the Carlton County Geologic Atlas, which will be published by the Minnesota Department of Natural Resources, will have a more thorough overview of bedrock aggregate and decorative stone resources, as well as an assessment of the surficial sand and gravel resources.

URANIUM

Carlton County was the focus of a brief but intense period of uranium exploration in the late 1970s to early 1980s. This exploration was spurred by the similarity in geologic environments to areas such as the Athabasca basin in northern Saskatchewan and other similar deposits in Australia, where known economic uranium deposits are present. In those places, uranium is concentrated along Proterozoic stratigraphic intervals where quartz-rich sandstones unconformably overlie older graphite- or carbon-bearing bedrock. The uranium is concentrated mainly within brecciated fault zones in the underlying basement or in areas where the basement was covered by sandstone prior to erosion, and to a lesser extent in breccia zones and pod-like concentrations in the overlying sandstone units. Occurrences of uranium mineralization are also present in Michigan, related to the unconformity between the Mesoproterozoic Jacobsville sandstone and the underlying Paleoproterozoic Michigamme Formation. These units are generally equivalent to the Fond du Lac Formation and the Thomson Formation, respectively, in east-central Minnesota. Phosphatic horizons in the Michigamme slate are also known to be uraniferous (Ojakangas, 1976).

The bedrock in Carlton County contains abundant carbonaceous and/or graphitic metasedimentary rocks of Paleoproterozoic age that are locally overlain by the Mesoproterozoic Fond du Lac Formation (sandstone), a setting very similar to that described above. Radioactivity levels of 10 to 20 times above normal background have been reported from brecciated graphitic slates near the *Arrowhead Mine* west of Mahtowa (Ojakangas, 1976), and although this area is some distance from the Fond du Lac Formation, it was probably covered by Fond du Lac Formation sandstone prior to erosion. Also, phosphatic nodules with elevated levels of uranium have been described in slate from the *Arrowhead Mine* area (McSwiggen and others, 1986). Although there has been no known uranium exploration activity in Carlton County since the 1980s, the seemingly favorable geologic setting could generate another cycle of exploration if future demand for nuclear power increases.

BASE METALS

Base metals, such as zinc, lead, iron, and copper, are commonly associated with volcanic and sedimentary rocks of many different ages, including Paleoproterozoic rocks similar to those in Carlton County. Many base metal deposits are one of two types: sedimentary-exhalative (SEDEX) and volcanogenic-massive sulfide. The composition and geologic setting of the bedrock in Carlton County is compatible with either of these deposit types, which has led to limited exploration activity and will likely lead to more activity in the future. The earliest exploration in Carlton County, by Hanna Mining and the U.S. Bureau of Mines, was for iron sulfide mineralization, and was based largely on targeting geophysical anomalies similar to those in the Glen Township and Cuyuna Iron Range to the west of Carlton County. Sporadic exploratory efforts from the 1990s were probably also based on targeted geophysical anomalies, most likely for the SEDEX style of mineral deposit.

SEDEX deposits are typically large, stratiform, massive sulfide bodies that form by the exhalative discharge of hydrothermal fluids onto the seafloor, or into permeable beds close to the seafloor. SEDEX mineralization is typically dominated by sphalerite (zinc sulfide) and galena (lead sulfide), along with pyrite and pyrrhotite (iron sulfides). These deposits are believed to typically form in relatively small, restricted oceanic basins that are filled with fine-grained, generally carbonaceous, clastic sedimentary rocks, within larger, rifted, continental basins. SEDEX deposits form by deeply circulating, hot fluids that leach metals such as zinc and copper from the underlying sediment pile. The metal-bearing brines rise up along basin-bounding faults as well as syndepositional faults within the seafloor sediments, and discharge at the seafloor, where the metals precipitate out of solution.

Most SEDEX deposits worldwide occur in rocks that range from 1,800 to 1,600 Ma in age, first appearing at about the time that deposition of Precambrian banded iron-formations, such as the Biwabik Iron Formation in Minnesota, ended (Lyons and others, 2006). Since at least some components of the Mille Lacs Group must be older than the circa 1,840 Ma metamorphic age obtained from them (Vallini and others, 2007), the bedrock in Carlton County that is thought to be part of the Mille Lacs Group, south of unit Etg, may be less likely to host SEDEX deposits than rocks deposited in the Animikie basin, the upper part of which was deposited as late as 1,777 Ma. Also, many of the sedimentary rocks in the Mille Lacs Group are closely associated with mafic volcanic rocks, an association generally not characteristic of SEDEX deposits. However, as interpreted by Southwick and others (2001), the geologic setting may still be favorable for occurrences of SEDEX mineral deposits. The barren Glen Township massive sulfide deposit, which is west of Carlton County, may be a SEDEX-like iron-sulfide deposit, via its association with deep-water clastic sedimentary rocks, chert, carbonate, and only moderately abundant mafic flows and sills. SEDEX deposits in general are associated with large quantities of pyrite and pyrrhotite, and the known large deposits in the Glen Township area of Aitkin County may be SEDEX-related. Given our currently poor understanding of bedrock ages in the Mille Lacs Group, which is thought to be a series of thrust-faulted structural panels, the area south of the Animikie basin should not be ruled out for SEDEX deposits. Alternatively, areas such as Kalevala Township (map unit Etm), situated at what here is mapped as the lower part of the Animikie basin, may post-date the Biwabik Iron Formation and thus might host SEDEX-style mineralization. For a more thorough review of SEDEX deposit characteristics, and isotopic data of rocks from Carlton County and east-central Minnesota, refer to Severson and others (2003).

Volcanogenic massive sulfide deposits form as lenses within submarine volcanic rock sequences and are generally smaller but higher-grade deposits dominated by copper, zinc, and lead. These deposits form by the exhalation of hot, metal-rich fluids driven by magmatic heat onto the seafloor, similar to black smoker deposits that are observed forming on the seafloor today. Volcanogenic massive sulfide deposits can form in a wide variety of tectonic environments that produce crustal extension, such as oceanic sea-floor spreading or back-arc basins. The basalts in Carlton County commonly contain pillow structures, evidence that they erupted in a submarine environment, and have a continental tholeiite composition, indicating they may have evolved in an extensional setting. However, most volcanogenic massive sulfide deposits are associated with bimodal mafic-felsic volcanism, and to date, no felsic volcanic rocks are known in east-central Minnesota.

The Glen Township massive sulfide deposit could be similar to a hybrid SEDEX-volcanogenic massive sulfide type of deposit known as *Besshi-style* or *pelitic-mafic*, which contains approximately equal proportions of fine-grained, calcareous to non-calcareous sedimentary rocks intercalated with mafic volcanic rocks. This type of deposit is most commonly hosted by rocks of late Proterozoic to Cretaceous (1,400 to 64 Ma) age, which are considerably younger than the rocks in Carlton County, but may provide an analogue exploration model.

ZINC ASSAY DATA

For the purpose of this study, new chemical analyses and assays were not obtained. Severson and others (2003), as part of a regional SEDEX zinc mineralization report, compiled available geochemical and assay data, which highlights some of the available zinc assay data and includes a more thorough description of the drilling history and style of mineralization. The localities listed below and shown on this map use the same locality names that were used in that report. The zinc values reported below are also summarized from that study.

- ***Arrowhead Mine***—At the *Arrowhead Mine*, several zinc values of approximately 1,000 to 5,000 parts per million (ppm) are reported, mostly from sooty black carbonaceous slate. Drill core MLCH-3 contained values of up to 4,200 ppm zinc over a 135-foot (41-meter) interval, and core MLCH-4 contained zinc values of up to 5,500 ppm over a 40-foot (12-meter) interval. Many other substantial zinc anomalies that were obtained from drill cuttings rather than drill core are thought to be of questionable accuracy. South of the *Arrowhead Mine*, drill core MLCH-11 is reported to contain an anomalous zinc value of 2,419 ppm from 334 to 335 feet (101.8 to 102.1 meters) depth within metagabbro (unit Egg), and drill core MLCH-9 contains 2,419 ppm zinc from 469 to 472 feet (143 to 144 meters) depth in pyritic-graphitic slate.
- **Kalevala Township**—Drill cores K-1 and KL-1 intersect beds within carbonaceous argillite, up to 2 centimeters thick and composed of 30 to 80 percent sulfides. The sulfide-rich layers are composed of very fine-grained pyrrhotite that locally contains delicately laminated sphalerite and chalcopyrite that may represent distal SEDEX-related deposits. There are also late brittle veins rich in sphalerite and/or chalcopyrite. Drill hole K-1 is reported to have zinc values of up to 2.25 percent (possibly related to vein, rather than bedded, sphalerite).
- **Kettle River area**—Carbonaceous/graphitic rocks in this area contain pyrite and pyrrhotite, with up to 30 percent total sulfides. Zinc analyses were obtained from four drill holes in this area, and several anomalous zinc values are reported from those holes, with reported values up to 4,717 ppm over a 10 foot interval in hole MG-7, and 3,300 ppm at 317 feet (97 meters) depth and 7,400 ppm from 339 to 340 feet (103.3 to 103.6 meters) depth in hole MG-5.
- **Split Rock area**—Seven cores in this area were analyzed for zinc; out of 70 samples there were 2 intervals in drill core MG-3 with zinc anomalies: 2,151 ppm at 272 to 274 feet (83 to 84 meters) depth in an interval of rubbly basalt flow-top, and 1,100 ppm at 374 to 382 feet (114 to 116 meters) depth in graphitic-pyritic slate.

IRON-FORMATION

There are no known iron-formations of significance in Carlton County, but there are known pyrite-pyrrhotite-rich metasedimentary rocks in many areas. Although these deposits contain iron, they are unlikely to be economical because of the difficulty in separating iron from the sulfide. They may, however, be associated with zinc mineralization.

SULFUR

Three diamond drill holes were drilled in 1950 and 1951 by the U.S. Bureau of Mines in T. 46 N., R. 20 W., sec. 7 to look for iron sulfide deposits as a source of sulfur, as a follow-up to reports of earlier drilling by unknown private interests that intersected sulfides (Pennington and Davis, 1953). These holes intersected carbonaceous slates with local pyrrhotite mineralization, similar to the Glen Township area in Aitkin County. No significant sulfur or base metal mineralization was reported by the U.S. Bureau of Mines in these holes. Subsequently, Hanna Mining drilled two holes in the general area of Kalevala Township, and three holes in Split Rock Township, also for sulfur and possibly base metals. All of these holes were situated over positive magnetic anomalies. Nearly all current domestic sulfur production is as a by-product of oil and gas refining processes, and it is unlikely that exploration for additional deposits of sulfur will take place in Carlton County.

TITANIUM AND RELATED ELEMENTS IN MESOPROTEROZOIC MAFIC INTRUSIONS

Titanium is used in a wide variety of applications including paint pigment, an alloy in high-strength metals, plastics, paper, and many others. One source of titanium is ilmenite ($FeTiO_3$), which commonly coexists with magnetite (Fe_3O_4) in mafic intrusions. The **Esko** oxide gabbro in Carlton County creates a strong, reversely-polarized magnetic anomaly, an indication that it contains substantial quantities of magnetite. This intrusion has attracted past exploration, and may be the focus of renewed exploration in the future, for titanium and possibly iron and/or other base metals. The Esko oxide gabbro is not exposed at the surface, but is covered by only 20 to 50 feet (6 to 15 meters) of glacial sediment.

The Esko oxide gabbro was reportedly drilled in 1966 by the W.S. Moore Company after completion of detailed ground geophysical surveys. Later, in that same area, Laurentian Enterprises drilled several additional holes, but apparently did not encounter significant mineralization (Ikola, unpub. data, 2009). The location and depth of the drill holes are unknown, as is the whereabouts of the drill core, and none of the information from those programs is known to be publicly available (see explanation for unit Eme on Plate 2, *Bedrock Geology*).

Most of the exposed Mesoproterozoic diabase dikes (unit Ed on Plate 2, *Bedrock Geology*; not shown on this plate) are very small and are unlikely to be considered for mineral exploration based on known mineral deposit models. However, the Cloquet dike (unit Edc on Plate 2, *Bedrock Geology*) and another parallel, unnamed dike to the northwest with a matching aeromagnetic signature, are of significant thickness and may conceivably contain mineralogical zonation or layering, which is an important attribute in mineralized intrusions. Also, the southwestern terminus of the Cloquet dike, as inferred from aeromagnetic data, passes through and apparently terminates in Paleoproterozoic rock units that are known from drill core to contain abundant pyrite and/or pyrrhotite. It is possible that emplacement of this thick diabase dike has redistributed and concentrated metals in those rocks.

BASE AND PRECIOUS METALS IN MESOPROTEROZOIC ULTRAMAFIC INTRUSIONS

Ultramafic intrusive rocks of Mesoproterozoic age (unit Emt; shown as the **Tamarack area** on this plate), located in western Carlton County, are likely continuous with similar rock types in adjacent Aitkin County that have been extensively drilled by the Kennecott Exploration Company. Kennecott identified a south-dipping zone of mineralization at least 2,461 feet (750 meters) long. According to a news release, they have delineated 9 to 11 million tons grading 1 to 1.1 percent nickel and 0.6 to 0.7 percent copper (base metals), with significant grades of platinum, palladium, and gold (precious metals). Mineralization is reported to be in the form of disseminated to massive sulfides within the ultramafic intrusion, as well as lenses of massive sulfide mineralization in the surrounding metasedimentary rocks. Although few details of this intrusion are currently made public, mineralization in the Tamarack intrusion is likely in part contact-style (Jirsa and others, 2006), formed by the intrusion of ultramafic magma into sulfidic country rocks (unit Etm). These sulfidic rocks may have provided a source for sulfur that has contaminated and saturated the magma with sulfide, concentrating metals in the contact zone. Work is continuing on this body to determine if the deposit will define a mineral resource.

Although the bulk of this drilling has taken place immediately west of Carlton County, at least seven holes have been drilled in the county to date and it is likely that more exploratory drilling will take place in the future.

SHEAR-ZONE HOSTED GOLD DEPOSITS

Other features that may attract interest are structural in nature, such as faults and shear zones mapped on the basis of geophysical data. Structures such as crustal-scale shear zones found throughout the world are host to several gold mining camps, in a wide variety of host rock types. A thorough overview of orogenic gold deposits is not presented here, but there are several overview papers available (for example Goldfarb and others, 2001; Bierlein and others, 2006). Thrust faults have been mapped in Carlton County based on presuppositions of the regional geology; however, the faults have poorly constrained locations and are largely conceptual. Although no exploration activity has been conducted in Carlton County based on this type of deposit model, it cannot be ruled out that at least limited exploration for this type of deposit may occur in the future as more details of the regional geologic structures emerge.

SUMMARY OF THE BEDROCK MINERAL ENDOWMENT OF CARLTON COUNTY

The bedrock in Carlton County has been moderately explored for different types of mineral deposits and their host metals, with limited success. However, the geologic environment and types of bedrock present in the county are still relatively poorly understood, despite the bedrock exposures and exploratory drill cores and cuttings samples available. Although high assay values for metals such as zinc have been found over small sample intervals, indicating potential metal resources, no mineable deposits have been found to date. Depending on the fluctuations in commodity prices, it is expected that exploration for metals such as zinc, copper, lead, and precious metals will continue.

Carlton County also has potential for crushed-rock aggregates given that there are exposures of bedrock types that may prove to be of suitable quality, especially in light of increasing costs of transporting high-quality aggregates from other areas of the state. Many of the schistose bedrock types also possess a strong flaggy parting that may make them desirable for use as landscaping stone.

GEOLOGIC ATLAS OF CARLTON COUNTY AND THE SOUTHERN PORTION OF ST. LOUIS COUNTY, MINNESOTA