Mineral Resource Database for Deposits Related to the Mesoproterozoic Midcontinent Rift System, United States and Canada

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U.S. Department of the Interior
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By Laurel G. Woodruff, Klaus J. Schulz, Connie L. Dicken, and Suzanne W. Nicholson

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
	Flow rate	
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)

Datum

Horizontal coordinate information is referenced to the World Geodetic System of 1984 (WGS 84).

Abbreviations

Ga	giga-annum (billion years ago)
GLIMPCE	Great Lakes International Multidisciplinary Program on Crustal Evolution
Ma	mega-annum (million years ago)
MDI	Mineral Deposit Inventory
MNDM	Ontario Ministry of Energy, Northern Development and Mines (Canada)
MPVG	Mamainse Point Volcanic Group
MRDS	Mineral Resources Data System
MRS	Midcontinent Rift System
NSVG	North Shore Volcanic Group
OUI	oxide-ultramafic intrusion
PGE	platinum-group element
PLV	Portage Lake Volcanics
REE	rare earth element
USGS	U.S. Geological Survey
USMIN	U.S. Geological Survey Mineral Deposit Database

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Abstract

The Midcontinent Rift System (MRS) of North America is one of the world's largest continental rifts and has an age of 1.1 Ga (giga-annum). The MRS hosts a diverse suite of magmatic and hydrothermal mineral deposits in the Lake Superior region where rift rocks are exposed at or near the surface. As part of the construction of a database summarizing information on mineral deposits in the MRS, data from regional mineral deposits were downloaded from the U.S. Geological Survey (USGS) Mineral Resources Data System (MRDS), the USGS Mineral Deposit Database (USMIN), and the Ontario Ministry of Energy, Northern Development and Mines Mineral Deposit Inventory (MDI). Deposits related to MRS rocks or mineralizing events were identified and compiled into a database to develop a space/time classification for MRS-related mineral deposits. Information from MRDS, USMIN, and MDI records and from the extensive literature describing MRS mineral deposits was used to classify each entry by deposit type, host rock age and type, and estimated mineralization age. Most deposits were readily classified because of unique mineralogy, location, or well-constrained host rock. These deposits were then put into a tectonic evolutionary framework for the MRS, which showed that many deposits formed within discrete spatial and temporal stages of rift evolution.

Introduction

The Mesoproterozoic Midcontinent Rift System (MRS) of North America is approximately 2,200 kilometers (km) long and is one of the world's largest continental rifts. It has a curvilinear shape that stretches from Kansas northeast to the Lake Superior region where it turns southeast and extends through Michigan (fig. 1). Although the rocks of the MRS are largely overlain by younger units, except in the Lake Superior region, the full extent of the MRS is highlighted by large positive aeromagnetic and gravity anomalies that were created by its huge volume of mafic volcanic and intrusive rocks (King and Zietz, 1971; Van Schmus and Hinze, 1985).

Rift volcanism lasted more than 20 million years, from about 1,112 Ma (mega-annum) to about 1,090 Ma, with minor eruptions lasting until about 1,083 Ma (Davis and Sutcliffe,1985; Palmer and Davis, 1987; Davis and Paces, 1990; Heaman and Machado, 1992; Paces and Miller, 1993; Davis and Green, 1997; Zartman and others, 1997; Vervoort and others, 2007; Swanson-Hysell and others, 2014; Fairchild and others, 2017; Swanson-Hysell and others, 2019). A conservative estimate of the volume of rift-related erupted basalt is 2 million cubic kilometers (km^3), possibly with an equal volume of intruded rock (Cannon, 1992). The large volume of MRS mafic igneous rocks as well as their geochemical and isotopic characteristics support the existence of a mantle plume as a source of thermal energy that helped create MRS melts (Hutchinson and others, 1990; Nicholson and Shirey, 1990; Nicholson and others, 1997). Seismic reflection profiles from the Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE) across the Lake Superior basin show that, during rifting, the Archean- to Paleoproterozoic-aged crust was thinned to less than half of its pre-rift thickness of about 50 km. The older crust was replaced by more than 20 to 25 km of rift-related basaltic lava flows overlain by up to 5 to 7 km of clastic sedimentary rock (see, for example, Behrendt and others, 1988; Cannon and others, 1989; Hutchinson and others, 1990).

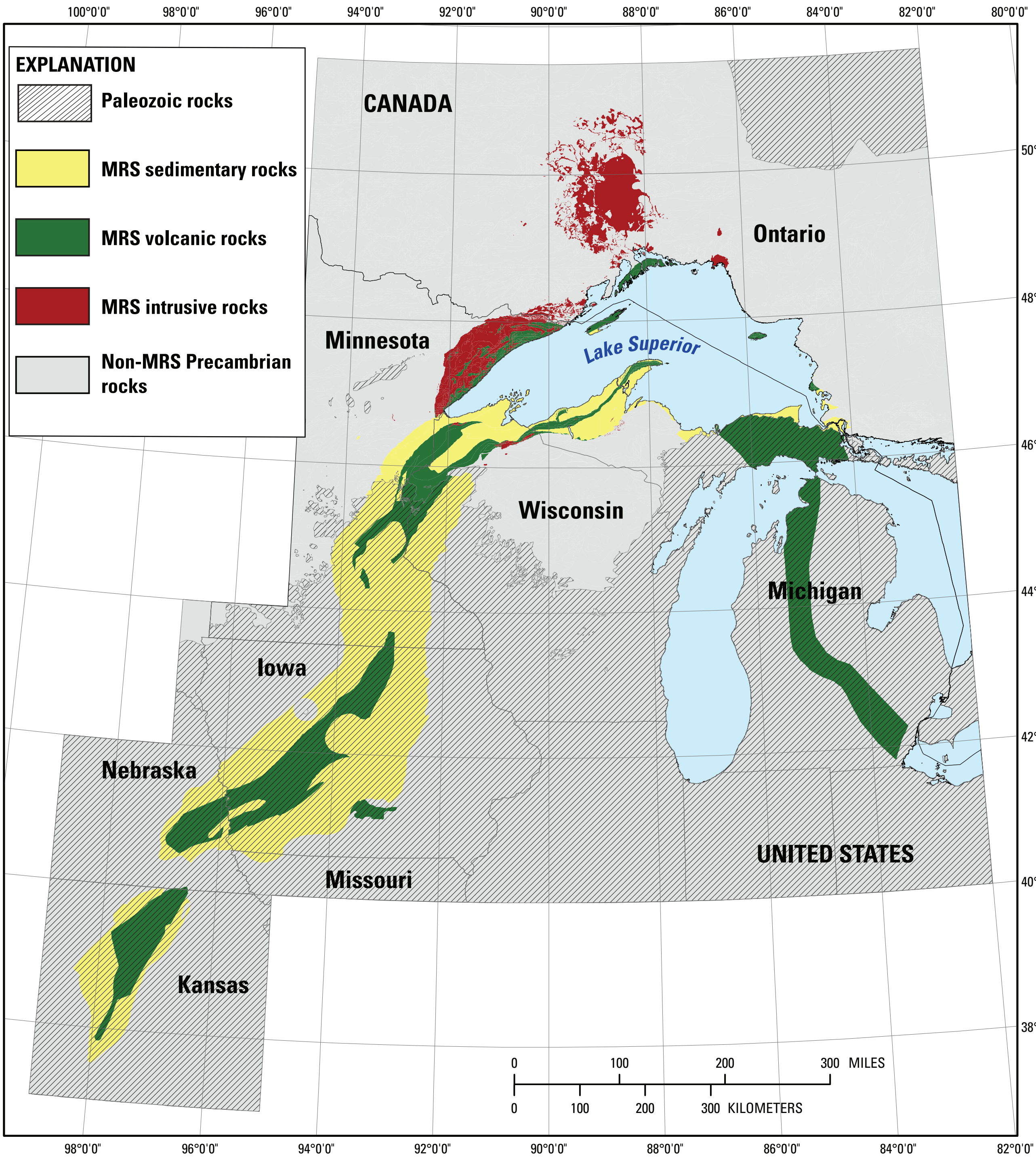

Figure 1. Map showing the distribution of major bedrock units of the Mesoproterozoic Midcontinent Rift System (MRS) in the northern United States and northern Ontario, Canada. The MRS cuts through Archean, Paleoproterozoic, and other Mesoproterozoic bedrock (the “Non-MRS Precambrian rocks” unit). Much of the area shown in the figure is overlain by younger Paleozoic bedrock (the “Paleozoic rocks” unit).

MRS Mineral Deposit Database

The MRS hosts a wide variety of magmatic and hydrothermal mineral deposits. The types of deposits reflect changing magmatic and tectonic events that marked the development and evolution of the MRS. An extensive literature describes MRS mineral deposits, both regionally and locally (see, for example, Cannon and McGervey, 1991; Nicholson and others, 1992; Miller and others, 2002; Smyk and Franklin, 2007; Miller and Nicholson, 2013). To capture information on these numerous and variable deposits, a comprehensive database summarizing MRS mineral deposits (table 1; available as a separate file) was compiled from the U.S. Geological Survey (USGS) Mineral Resources Data System (MRDS; U.S. Geological Survey, 2011) and the Ontario Ministry of Energy, Northern Development and Mines (MNDM) Mineral Deposit Inventory (MDI; Ontario Ministry of Energy, Northern Development and Mines, 2019). MRDS is a searchable collection of archived reports that describe metallic and nonmetallic mineral resources of the United States and other countries. Data include deposit name, location, commodity, deposit description, and geological characteristics. However, MRDS is no longer supported by the USGS and is being replaced by the USGS Mineral Deposit Database (USMIN; U.S. Geological Survey, 2019), an updated national mineral deposit database. Deposit information in the Ontario MDI includes deposit name, occurrence type, and primary and secondary commodities. Deposits in MRDS and the MDI are included in this compilation; three additional deposits recognized through recent exploration that are in USMIN (Burger and others, 2018) are included here for completeness.

A few known MRS-related deposits described in recent literature that are not listed in MRDS, USMIN, or the MDI are not included in table 1. In addition, several MRDS entries for the commodity “copper” in Michigan and Wisconsin—many of which refer to native copper mineralization in MRS basalts—are called “unnamed copper prospect” or “unnamed copper deposit” or “unnamed copper mine.” All such entries have sparse information and are ranked with a quality grade of “D” (out of a scale ranging from “A” to “E,” where “A” is a most reliable and informative record and “E” is a least reliable and informative record) (Schweitzer, 2019). Because of their low quality, these records are not included in table 1.

Structure of the MRS Mineral Resource Database

The compiled MRS mineral resource database (table 1) lists 495 individual mineral prospects, occurrences, producers, and past producers that are characterized by columns of descriptive information. All but three columns contain explanatory information derived from MRDS, USMIN, or the MDI. These data attributes include:

- a unique entry identifier assigned by either MRDS (column A), USMIN (column B), or the MDI (column C);
- deposit name (column D) and alternate name(s) (columns E and F);
- deposit category (column G) (see appendix 1 for an explanation of categories);
- country (column H);
- State or Province (column I);
- county, township, or area (column J);
- location defined by latitude and longitude coordinates expressed in decimal degrees (datum: World Geodetic System 1984 [WGS84]) (columns K and L);
- major commodities in order of their relative economic importance (columns M and N);
- minor commodities in order of their relative economic importance (columns O through R);
- ore mineralogy (if known) in order of their relative economic importance (columns S through X);
- gangue mineralogy (if known) (columns Y through AC);
- tectonic setting (inferred from host formation; column AD);
- host rock lithology, formation name, and age (if known) in order of their relative economic importance (columns AE through AJ); and
- associated rock lithology, formation name, and age (if known) (columns AK, AL, and AM).

The final three columns in the database (table 1) contain our interpretation of each deposit’s place in MRS space/time groupings. The entries in these three columns were informed by data in MRDS, USMIN, and the MDI, as well as by the extensive MRS mineral deposit literature. These last three columns are the focus of this publication:

- deposit class, defined as magmatic, hydrothermal, or magmatic-hydrothermal (column AN);
- MRS tectonic development stage during which the deposit formed (column AO); and
- specific name for a descriptive deposit type (column AP).

Deposit Class

Attributes in column AN of the database (table 1) describe the deposit class for the mineral deposits. Most deposits are easily classified as either “magmatic” or “hydrothermal” based on mineralogy, setting, and the nature of host rocks. Magmatic deposits can form directly in place from a melt or consist of minerals crystallized from and transported by melt. These deposits are genetically related to their host rocks, and thus the mineralization age is the same as or is very close to the age of the host rocks. In contrast, hydrothermal deposits form by precipitation from hot metal-bearing fluids. Because fluids and metals may have originated far from the deposit, the timing of mineralization is often poorly constrained when compared with the timing of magmatic deposits. Deposits classified as “magmatic-hydrothermal” represent a hybrid of the two processes. Intruded magma can release high-pressure, metal-bearing magmatic fluids that hydrofracture the overlying country rock. Mineralization in a permeable, veined, and brecciated carapace can result from mixing of magmatic and local hydrothermal or meteoric waters, and (or) a decrease in temperature and (or) pressure. Although mineralization often is distal to an intrusion, the timing of mineralization in these hybrid systems is closely related to the timing of related intrusive events.

MRS Tectonic Development Stage

Attributes in column AO of the database (table 1) identify our assigned tectonic development stages of the MRS. Based on age, physical volcanology, magnetic polarity, and geochemistry of MRS rocks in the Lake Superior region, three main magmatic stages of rift development are delineated: the early Plateau Stage (~1,112 to ~1,105 Ma), followed by the Rift Stage (~1,102 to ~1,090 Ma), and the Late-Rift Stage (~1,090 to ~1,083 Ma). Prior to high precision uranium-lead (U-Pb) zircon dating, the magnetic polarity of MRS rocks was a major tool used to distinguish what is now named the early Plateau Stage from the later Rift Stage. Extensive characterization of the magnetic properties of MRS rocks (Books, 1972; Halls and Pesonen, 1982) showed that early MRS Plateau Stage basalts and intrusions mainly have reversed magnetic polarity, whereas the more voluminous Rift Stage flood basalts and intrusions have normal magnetic polarity. The change from reversed to normal magnetic polarity may have fluctuated over a short interval between about 1,102 Ma and 1,100 Ma (Swanson-Hysell and others, 2014); however, MRS rocks dated at ~1,102 Ma and older have reversed magnetic polarity and rocks dated at ~1,100 Ma and younger have normal magnetic polarity. This difference makes magnetic polarity of undated rock units (if known) a very useful tool for tectonic stage classification.

Two additional stages of rift evolution are important for mineralization related to the MRS. The Post-Rift Stage (~1,083 to ~1,060 Ma) represents a time interval dominated by clastic sedimentation between the older Late-Rift Stage and a younger Compressional Stage (~1,060 to ~1,040 Ma), which was a time of prolonged tectonic activity. All stages are described in more detail below.

Deposit Type

Attributes in column AP in the database (table 1) describe our deposit type names for each of the entries. The 495 MRS-related mineral deposits in this database are classified into specific deposit types based on host rock, deposit characteristics, dominant commodities, and metal affinities. Individual deposit types are assigned to an MRS tectonic stage based on a combination of host rock age or magnetic polarity, mineralization age, and cross-cutting relationships. For some deposit types, detailed geologic descriptions in published literature were critical to distinguishing among them.

For example, the Eagle deposit in Michigan, now an operating nickel mine, is hosted by an MRS reversed-magnetic-polarity ultramafic intrusion that has a crystallization age of 1,107.2±5.7 Ma (Ding and others, 2010). It is described by Schulz and others (2014) as a conduit-type nickel-copper-platinum-group element (Ni-Cu-PGE) sulfide deposit. Thus, the Eagle deposit is classified by its deposit class (Magmatic; column AN), MRS tectonic development stage (Plateau Stage; column AO), and specific deposit type (Conduit-type Ni-Cu-PGE Sulfide; column AP).

MRS Tectonic Stages and Related Mineral Deposit Types

Plateau Stage Characteristics

The early Plateau Stage of MRS development extended from ~1,112 to ~1,105 Ma. MRS volcanic activity in western Lake Superior began with the eruption of high-magnesium pyroxene-phyric basalt onto a thin layer of mature quartz sandstone. Compositions of the earliest MRS basalt in western Lake Superior are consistent with low-percentage partial melts (~1 to 3 percent) produced near the base of the lithosphere at depths of ≥120 km (Schulz and Nicholson, 2016). Lateral and stratigraphically higher contrasting basalt compositions denote melting at shallower depths of ≤80 km (Schulz and Nicholson, 2016). Such rapid transitions in melting depths are consistent with a subcrustal lithosphere in the Lake Superior region that was of variable thickness prior to the development of the MRS (Faure and others, 2011).

During this early stage, subaerial basalts erupted from fissures and low-angle shield volcanoes across a broad area to form a ≤10-km-thick volcanic plateau (Green, 1989). There is little evidence of actual rifting during the Plateau Stage (Green, 1983; Allen and others, 1995), although basalt sequences appear to thicken toward the eventual rift axis in Lake Superior. Intrusions of sills and plutons accompanied volcanic eruptions. The original spatial extent of Plateau Stage lava flows is unknown because their terminations outward from the Lake Superior region are extensively eroded (Cannon, 1992). The distribution of magnetically reversed dikes, however, is evidence that Plateau Stage basalts extended south beyond the Lake Superior region into Minnesota and central Wisconsin (Green and others, 1987).

In Ontario, Canada, alkaline intrusions were emplaced into rocks of the Archean Superior Province, and diabase sills intruded conformably into flat-lying Paleoproterozoic and early Mesoproterozoic sedimentary sequences. In northeastern Minnesota, gabbroic layered intrusions and granophyric felsic bodies marked the beginning of intrusive magmatic activity that would result in the formation of the large Duluth Complex (Miller and others, 2002).

Plateau Stage Magmatic Mineral Deposits

Conduit-Type Nickel-Copper-PGE Sulfide

Conduit-type Ni-Cu-PGE sulfide deposits are defined as magmatic sulfide mineralization restricted to small- to medium-sized (typically hundreds of meters to several kilometers thick and hundreds of meters to tens of kilometers long), mafic and (or) ultramafic, irregularly shaped sills, dikes, or chonoliths that served as pathways for the flow-through of picritic and (or) magnesium-rich basaltic magmas (Schulz and others, 2014). Conduit-type sulfide deposits often contain more metal and sulfur than could be derived just from the limited volume of magma that formed their host intrusions. This implies that the sulfide deposits were derived from a much greater volume of magma than the current volume of the intrusions that host them. Thus, the sulfide deposits represent the product of a large volume of magma that moved through open conduits and enriched an immiscible sulfide liquid with metals. Economic minerals in conduit-type deposits are primarily pentlandite, chalcopyrite, and pyrrhotite (Schulz and others, 2014).

Examples of this deposit type in the MRS include the Eagle deposit in northern Michigan (the only operating primary nickel mine in the United States since production began in 2014), the Tamarack deposit in east-central Minnesota, and the Thunder Bay North (also known as Current Lake) deposit in northern Ontario. The mineralized Eagle East intrusion is a possible extension of the mineralized Eagle intrusion, although drilling has not located any shared feeder connections. These metal-rich deposits typically vary from massive to semi-massive sulfide to disseminated sulfide with Ni>Cu and have only been found outside the central MRS rift where they intrude older basement rocks.

The Marathon Series of the Coldwell Complex is host to several Cu-Ni-PGE mineralized gabbroic and ultramafic intrusions, including the Two Duck Lake, Geordie Lake, and Area 41 intrusions (Good and Lightfoot, 2019). The Marathon Cu-PGE sulfide deposit in the Two Duck Lake intrusion has a different metal endowment than the other known conduit-type sulfide deposits, such as Eagle or Tamarack, as it has little or no Ni and extreme local enrichment of PGE (Good and others, 2015). Mineralization is thought to have developed by multiple injections of crystal mush carrying sulfide droplets; thus, the Marathon Cu-PGE deposit is described as a conduit-type sulfide deposit (Good and others, 2015), although it differs in detail from other MRS sulfide deposits of this type.

Host rocks for MRS Ni-rich conduit-type sulfide deposits are the product of the high magnesium magmas that erupted only during the Plateau Stage of rift development (Nicholson and others, 1997; Ding and others, 2010; Taranovic and others, 2015). Dates of intrusions that host conduit-type deposits are 1,107.2±5.7 Ma for the Eagle deposit (Ding and others, 2010) and 1,105.6±1.2 Ma for the Tamarack deposit (Goldner, 2011). Recent dates for gabbro intrusions that host the Marathon Cu-PGE deposit are reported to be between 1,107.7±2.1 Ma and 1,106.1±2.2 Ma (Good and Lightfoot, 2019).

Layered Iron-Titanium Oxide

Layered Fe-Ti (iron-titanium) oxide mineralization occurs as banded segregations in the reversed-magnetic-polarity Poplar Lake intrusion, a large layered intrusion of dominantly gabbroic cumulates along the northeastern contact of the Duluth Complex, Minnesota. The intrusion was dated at 1,106.9±0.6 Ma (Paces and Miller, 1993). Grout (1950) described drill core from the intrusion as a series of olivine gabbro layers grading to peridotite layers, with intervening segregations of magnetite-ilmenite oxides. Some oxide layers have up to 35 percent iron and 18 percent titanium dioxide (Grout, 1950).

Alkalic-Hosted Uranium-Niobium±Rare Earth Elements

In northern Ontario, along the trend of the Big Bay-Ashburton fault—which Sage (1991) proposed was part of a much larger, generally north-south-trending Trans-Superior Tectonic Zone—is a series of diatremes, alkalic intrusions, and carbonatites. Among these are the alkalic Coldwell Complex, the Dead Horse Creek diatremes, and the Killala Lake Complex. In addition to sulfide mineralization, the Coldwell Complex has radioactive columbite-bearing syenite dikes along fractures that cut mafic intrusions (Scott, 1987). The Dead Horse Complex is a diverse group of highly altered heterolithic breccias that is being explored for uranium and rare earth elements (REEs) (Zurevinski and others, 2019). The Killala Lake intrusion has a syenite core surrounded by a rim of olivine gabbro; pegmatitic phases of the syenite contain pyrochlore (Sage, 1988).

Miscellaneous Magmatic Sulfide

This group of magmatic sulfide-bearing mineral occurrences hosted by Plateau Stage intrusive rocks is not well characterized, although further exploration may better define its nature. Occurrences include sulfide mineralization within or near small mafic-ultramafic intrusions, such as Disraeli, Hele, and Seagull, all of which are in the Nipigon Embayment, Ontario (Hart and MacDonald, 2007). The Disraeli intrusion has been dated at 1,109±1.4 Ma, the Hele intrusion has been dated at 1,106.6±1.5 Ma, and the Seagull peridotite intrusion has been dated at 1,112.8±1.4 Ma (Heaman and others, 2007). Additional Plateau Stage magmatic sulfide deposits and occurrences include Fairbairne and Geordie Lake in the Coldwell Complex (~1,108 Ma) and Sandspit-Papaver in the Killala Lake Complex (undated).

Rift Stage Characteristics

A second magmatic stage, the Rift Stage, is constrained between ~1,102 and ~1,090 Ma. Following an interval of little apparent magmatic activity, rifting began with voluminous subaerial flood basalt eruptions within rapidly subsiding basins along the trend of modern Lake Superior and along the eastern and western arms of the MRS. Basalt compositions changed from magnesium-rich during the Plateau Stage to aluminum-rich during this Rift Stage. Rift Stage basalt compositions throughout the Lake Superior region are generally similar and consistent with large quantities of melting at a relatively shallow depth (~45 km).

Eruptions were generally very frequent over the given timescale, with individual lava flows commonly occurring one after the other and keeping pace with subsidence such that successive flows erupted onto relatively flat surfaces (White, 1960). Along the Keweenaw Peninsula in northern Michigan, the 5-km-thick Rift Stage Portage Lake Volcanics (PLV) is composed of more than 200 individual basalt flows, many of which are remarkably uniform in terms of thickness and strike length (White, 1960). Swanson-Hysell and others (2019) used precise dating to estimate median eruption rates of 1.2 millimeters per year (mm/yr) for the PLV and 2.1 mm/yr for normal magnetic polarity basalts of the North Shore Volcanic Group (NSVG) in northeastern Minnesota. Breaks in volcanism are indicated locally by the presence of sedimentary interflow conglomerate and sandstone units, several of which can be followed along strike for more than 100 km (Merk and Jirsa, 1982). These interflow sedimentary units are consistent time markers in the Rift Stage volcanic section in western Lake Superior, help to constrain flow stratigraphy along strike, and are an important host rock to hydrothermal native copper deposits in Michigan (Butler and Burbank, 1929).

Rift Stage mafic intrusions into the middle and upper crust formed the Duluth and Beaver Bay Complexes in Minnesota and the Mellen Complex in Wisconsin. Rift Stage Duluth Complex intrusions are tightly constrained between 1,099 Ma and 1,098 Ma (Paces and Miller, 1993). Intrusions of the Duluth Complex are at the surface along its western margin, but the lower contact plunges southeastward beneath a carapace of the NSVG and the younger Beaver Bay Complex. The Beaver Bay Complex consists of mostly non-cumulate, hypabyssal mafic intrusions emplaced into the NSVG package (Miller and Chandler, 1997). Two intrusions from the Beaver Bay Complex have been dated at 1,096.1±0.8 Ma and 1,095.8±1.2 Ma (Paces and Miller, 1993).

The timing of declining Rift Stage subaerial volcanism is established by the Greenstone flow in the upper part of the Portage Lake Volcanics. A recently published date for differentiated pegmatite in the flow is 1,091.59±0.27 Ma (Swanson-Hysell and others, 2019). Conglomerates indicating a shift in rift behavior from mainly magmatic to mainly sedimentary are only ~600 meters (m) stratigraphically above the Greenstone flow, which suggests that Rift Stage magmatism may have ended around 1,090 Ma.

Rift Stage Magmatic Mineral Deposits

Contact-Type Copper-Nickel-PGE Sulfide

Contact-type Cu-Ni-PGE sulfide deposits (Zientek, 2012) are exemplified by mainly disseminated sulfide mineralization along the basal contacts between MRS Rift Stage intrusions and Paleoproterozoic and Archean country rock. Interstitial disseminated sulfides—including pyrrhotite, chalcopyrite, cubanite, and pentlandite—can be extremely erratic in spatial extent and ore grades along the basal units of the intrusions (Miller and others, 2002). Rift Stage contact-type sulfide deposits have Cu>Ni likely because Rift Stage magmas were lower in MgO (magnesium oxide) and richer in aluminum than magmas of the Plateau Stage that gave rise to the conduit-type Ni-Cu±PGE sulfide deposits.

There are currently 11 identified contact-type sulfide deposits along the basal contact of the Duluth Complex where the South Kawishiwi, Bathtub, and Partridge River intrusions are in contact with Animikie Group metasedimentary rocks and Late Archean igneous, sedimentary, and metamorphic rocks (Miller and others, 2002). Major named deposits include Birch Lake, Dunka Pit, Maturi, Mesaba, NorthMet, Serpentine, and Spruce Road. Disseminated and local more massive sulfide mineralization of the Duluth Complex is estimated to contain about 4.4 billion metric tons of ore with average grades of 0.66 percent Cu and 0.2 percent Ni at a 0.5-percent Cu cut-off (Listerud and Meineke, 1977). Contact-type disseminated sulfide mineralization—consisting of chalcopyrite, cubanite, and pentlandite in thin patches and veinlets—also occurs near the base of the Mellen Complex in Wisconsin where it is in contact with the Paleoproterozoic Tyler Formation, a unit equivalent to the Virginia Formation.

Titanium-Iron Oxide

Titanium-iron oxide mineralization in normal magnetic polarity Duluth Complex intrusions is found in two spatially separated areas. The most important titanium-iron±vanadium (Ti-Fe±V) oxide deposits are late, discordant intrusions along the southern basal section of the Duluth Complex. These bodies are called oxide-ultramafic intrusions, or OUIs, and are pegmatitic, plug- and dike-shaped intrusive bodies that cut the Partridge River Intrusion and other Duluth Complex intrusions to the south (Severson, 1988). Deposits including Longnose, Longear, and Water Hen also carry minor Cu-Ni sulfide mineralization. Several OUIs are in faults or are close to fault zones, typically with nearby inclusions of Biwabik Iron-Formation (Hauck and others, 1997). These relationships suggested to Severson (1988) that there was a genetic connection between OUI Ti-Fe±V mineralization and inclusions of iron-formation. A separate group of titaniferous magnetite deposits along the northern basal contact of the Duluth Complex was interpreted to be the product of alteration and metamorphism of inclusions of the Paleoproterozoic Gunflint Iron-Formation (equivalent to the Biwabik Iron-Formation) by Duluth Complex magma (Broderick, 1917; Grout, 1950). One puzzling aspect of both types of Ti-Fe oxide mineralization, if it is related to assimilation of iron-formation, is the relatively high Ti content of the oxides, as iron-formation typically has very low Ti content (Broderick, 1917; Hauck and others, 1997).

Miscellaneous Magmatic Sulfide

Locations of massive to disseminated chalcopyrite and pyrrhotite mineralization, some known only from limited exploration drilling, are related to MRS gabbro and diabase dikes south of the Thunder Bay region, Ontario (Lightfoot and Lavigne, 1995; Smyk and Franklin, 2007). Most of the dikes, such as the Pigeon River swarm, have normal magnetic polarity; thus, these deposits are included in the MRS Rift Stage. The largest known deposit in the region is the Great Lakes Nickel Cu-Ni deposit in the Crystal Lake Gabbro. The Crystal Lake Gabbro is an approximately Y-shaped intrusion about 5 km long with a shorter 2.75-km-long arm extending to the southeast (Smith and Sutcliffe, 1987). A date for the intrusion is 1,099±1.2 Ma (Heaman and others, 2007). Mineralization at Crystal Lake has characteristics similar to contact-type sulfide deposits of the Duluth Complex (for example, intrusion age, sulfide mineralogy, disseminated sulfides with Cu>Ni; see Cogulu, 1993). However, the intrusion's small size and internal layering of the northern limb—which suggests a tilted cone open on the western end (Smith and Sutcliffe, 1987)—are more similar to host intrusions of conduit-type sulfide deposits.

Late-Rift Stage Characteristics

With the end of voluminous magmatic activity, subsidence within the central rift basins continued due to thermal relaxation as mantle plume heat and intrusive activity waned (Cannon and Hinze, 1992). The Late-Rift Stage, from ~1,090 to ~1,083 Ma, was a time of diminishing magmatism and increasing sedimentation. The shift to a sedimentary regime began with the deposition of coarse conglomerates in alluvial fans into the central rift region sourced from highlands away from the rift basins. This early sedimentary sequence is called the Copper Harbor Formation, which is composed of coarse conglomerate and red sandstone and has a maximum exposed thickness of ~2 km (Daniels, 1982).

There was localized volcanism around Lake Superior during this stage. Near the end of the Keweenaw Peninsula, the Lakeshore Traps in the Copper Harbor Formation are made up of ~60 individual lava flows which are 1 to 30 m thick and range in composition from tholeiitic basalt to andesite. Davis and Paces (1990) obtained a $^{207}Pb/^{206}Pb$ date of 1,087.2±1.6 Ma for an andesite flow in the Lakeshore Traps; Fairchild and others (2017) obtained a more precise $^{206}Pb/^{238}U$ date of 1,085.57±0.25 Ma for the same andesite flow. Products of late felsic volcanism in eastern Lake Superior include felsic porphyrite and a rhyolite flow on Michipicoten Island; their emplacements have been dated at 1,086.5+1.3/-3.0 Ma (Palmer and Davis, 1987) and 1,083.52±0.23 Ma (Fairchild and others, 2017), respectively. Rhyolite at a depth of 7,238 feet (2,206 meters) near the base of a borehole in Michigan's eastern Upper Peninsula was dated at 1,083.0±3 Ma (Ojakangas and Dickas, 2002). The Schroeder-Lutsen tholeiitic basalt sequence, the youngest flows of the NSVG in Minnesota, are unconformable on older volcanics and are likely younger than 1,091.61±0.14 Ma (Fairchild and others, 2017), a date for the Silver Bay intrusion in the Beaver Bay Complex that is overlain by the Schroeder-Lutsen sequence.

Late-Rift Stage Magmatic-Hydrothermal Mineral Deposits

The three deposit types listed in this section are within or near the MRS Mamainse Point Volcanic Group (MPVG), a 6-km-thick sequence of basalt flows, rhyolites, and conglomerates along the eastern Lake Superior shoreline that unconformably overlies an Archean granite-greenstone terrane. Mineralization near Mamainse Point is associated with local MRS-related felsic intrusions and cross-cutting felsite dikes. The area is also cut through by a series of mineralized quartz veins and breccia pipes that are thought to be cogenetic, which would indicate different levels of exposure of a porphyry-related hydrothermal system (Richards and Spooner, 1989). The three deposit types listed below are from shallow to deep in the mineralization sequence of Richards and Spooner (1989).

The timing of this felsic volcanism and mineralization during the Late-Rift Stage is not well constrained by modern dating methods. Roscoe (1965) reported a potassium-argon (K-Ar) date of 1,055±55 Ma for muscovite from the mineralized Breton pipe breccia in the Tribag area. Two samples from drill core into the Jogran porphyry yielded a rubidium-strontium (Rb-Sr) date of 1,070±50 Ma (Van Schmus, 1971).

Copper Sulfide-Bearing Quartz Veins

Copper sulfide-bearing quartz veins that make up the Coppercorp and Lutz deposits (two epigenetic vein sets) cut basalt flows of the MPVG. Mineralization is mainly chalcocite with minor bornite, chalcopyrite, and silver in quartz- and carbonate-filled cross-cutting veins. Between 1965 and 1972, the Coppercorp mine produced about 1.3 million tons of ore at 2.1 percent copper (Grunsky, 1991). Fluid inclusion data from the Coppercorp deposit suggest that hydrothermal mineralization in these deposits was related to the same intrusive activity that created the Jogran porphyry and copper-molybdenum±gold (Cu-Mo±Au) breccia pipes (Richards and Spooner, 1989).

Copper±Molybdenum Porphyry

Copper±molybdenum porphyry mineralization is related to the Jogran intrusion that contains quartz and feldspar phenocrysts. The Jogran porphyry has a surface outcrop of ~200 m by 120 m; drilling into the porphyry reached a depth of ~200 m, but the true dimensions of the intrusion are unknown (Armbrust, 1980). The Jogran porphyry, one of several in the area, is pervasively mineralized with disseminated chalcopyrite and minor molybdenite along its margins; narrow quartz veins that cut the porphyry also carry molybdenite flakes (Blecha, 1974). The average grade of the Jogran porphyry is 0.19 percent Cu and 0.032 percent Mo, with locally high grades of silver (Ag) up to 2.08 ounces per ton (Grunsky, 1991).

Copper-Molybdenum±Gold Breccia Pipe

Copper-molybdenum±gold breccia pipes developed over MRS felsic intrusions that cut an Archean granite-greenstone terrane (Armbrust, 1969; Norman and Sawkins, 1985). Five separate breccia pipes are recognized along a 2-km trend, but only two (Breton breccia and West breccia) have supported mining. From 1967 until 1974, the Tribag Mining Company produced 16,900 metric tons of copper and 246,000 ounces of silver from the Breton breccia (Grunsky, 1991). Drilling in 1974 identified the Palmer breccia, which is about 6 km southwest of the Tribag area. Breccias contain angular fragments of granite, diabase, felsite, and metavolcanic rock, all of which were locally derived (Blecha, 1974). Exploration through the Breton breccia pipe encountered a quartz-feldspar porphyry at about 600 m depth (Norman and Sawkins, 1985). The spatial relationship to felsic intrusions, sulfide mineralogy, and fluid inclusions, as well as stable isotope data, led Norman and Sawkins (1985) to conclude that the major component of mineralizing fluids at the Tribag district was most likely magmatic, related to local porphyry intrusions.

Post-Rift Stage Characteristics

Two additional stages of rift evolution are important for mineralization related to the MRS. The Post-Rift Stage represents the time interval between the Late-Rift Stage (which we estimate ended at ~1,083 Ma) and the Compressional Stage (~1,060 to ~1,040 Ma). The sedimentary sequence that began with the deposition of the Copper Harbor Formation during the Late-Rift Stage was followed by a marine or lacustrine incursion which resulted in the deposition of the ~240-m-thick Nonesuch Formation (Daniels, 1982). The Nonesuch Formation is overlain by a sequence of clastic sediments (the ~1,500- to ~3,600-m-thick Freda Formation; Daniels, 1982). Both the Nonesuch and Freda Formations were deposited into subsiding central rift basins. The sedimentary sequence of the Copper Harbor, Nonesuch, and Freda Formations is called the Oronto Group. A synsedimentary carbonate bed in the Nonesuch Formation has a Pb-Pb isochron date of 1,081±9 Ma (Ohr, 1993); a composite sample collected from outcrop yielded a less precise rhenium-osmium (Re-Os) depositional age of 1,078±24 Ma (Cumming and others, 2013), which overlaps the age obtained by Ohr (1993). The top of the Freda Formation is not exposed and it is overlain by unconformable sandstone units (all possibly somewhat time equivalent) including the Bayfield Group in Wisconsin, the Jacobsville Sandstone in Michigan and Ontario, and the Fond du Lac and Hinkley Formations in Minnesota.

Late-Rift Stage and Post-Rift Stage Hydrothermal Mineral Deposits

Hydrothermal mineral deposits have been the most productive MRS deposits to date in terms of metrics like total value and volume of metal extracted; however, exploration, development, and production in the region are shifting to magmatic sulfide deposits. The broad array of MRS hydrothermal deposits are classified based on ore mineralogy, setting, and age, with some groups containing multiple, more specific deposit types. For many of these deposits, there are few definitive constraints on the timing of mineralizing events.

Veins in the Thunder Bay Area, Northern Ontario

In the Thunder Bay area in northern Ontario, MRS rocks include sills from the Plateau Stage as well as dikes from the Rift Stage. The Logan sills intruded into flat-lying siltstone and shale of the Paleoproterozoic Rove Formation and Gunflint Iron-Formation of the Animikie Group and the Nipigon sills intruded into flat-lying sandstone of the early Mesoproterozoic Sibley Group. Northeast-southwest-trending Rift Stage Pigeon River dikes parallel the Lake Superior shoreline. A later generation of northwest-southeast-trending dikes cut the Pigeon River dike swarm (Cundari and others, 2011).

Mainland Group Silver-Bearing Veins

Silver-bearing veins near Thunder Bay are often called the Mainland group to distinguish them from polymetallic silver-bearing veins called the Island group. Mainland group silver mineralization is within an area where MRS Plateau Stage Logan diabase sills conformably intruded into the lower section of the Paleoproterozoic Rove Formation. Mineralization in veins occupies fault sets that are roughly parallel to the Archean/Proterozoic boundary, cutting both diabase and Rove shale and siltstone (Franklin and others, 1986). Silver occurs as the native metal and as acanthite accompanied by galena, sphalerite, pyrite, and chalcopyrite, with a gangue of calcite, quartz (sometimes amethystine), barite, and fluorite (Sergiades, 1968).

Island Group Polymetallic Silver-Bearing Veins

Polymetallic silver-bearing veins in the Island group occur where Rove Formation greywacke and shale were intruded by a swarm of mainly east-northeast-striking Rift Stage diabase dikes. Veins in northwest-trending faults perpendicular to the strike of the dikes host silver deposits along the shore and on several islands of Lake Superior, including the large vein exploited by the Silver Islet mine located on a small island in Lake Superior off the tip of the Sibley Peninsula. Ores in the Island group are characterized by native metals and a unique group of five elements: silver-bismuth-cobalt-nickel-arsenic (Ag-Bi-Co-Ni-As) (Tanton, 1931; Kissin, 1992). Ore minerals for the polymetallic veins include native silver and argentite, as well as niccolite, galena, sphalerite, marcasite, cobaltite, skutterudite, domeykite, chalcopyrite, and tetrahedrite, with a gangue of dolomite and quartz (Tanton, 1931). Silver-bearing veins in the Mainland and Island groups produced 300,000 pounds of native silver in the mid- to late-1800s, with the Silver Islet mine being accountable for more than 60 percent of this total production (Franklin and others, 1986).

Lead-Zinc-Silver Veins

Lead-zinc-silver veins, also called the Port Coldwell veins, are in an area of sheared Archean metasedimentary rocks and metavolcanic rocks cut by MRS dikes that are likely related to the Coldwell Complex (~1,108 Ma). Lead-zinc-silver-bearing veins are commonly in north-south faults that cut all rock types. These deposits contain argentiferous galena and sphalerite, along with pyrite, chalcopyrite, covellite, and digenite (McCuaig and Kissin, 1997).

Amethyst-Bearing Veins

Gem-quality amethyst crystals are being mined from parallel and subparallel north- northeast-trending brecciated vein systems that cut Archean and Sibley Group rocks near the unconformity between the two units (Smyk and O'Brien, 1991; Garland, 1994). Veins are typically zoned with multiple generations of chalcedony, quartz, and amethyst, along with secondary chlorite, hematite, and calcite, and more rarely chalcopyrite, galena, sphalerite, and pyrite (McArthur and others, 1993; Garland, 1994). Amethyst also occurs in lead-zinc-barite veins.

Lead-Zinc-Barite Veins

Lead-zinc-barite veins mainly carry galena and sphalerite with minor pyrite, marcasite, chalcopyrite, and chalcocite in a gangue of quartz (locally amethystine), calcite, barite, and minor fluorite. Galena, sphalerite, and chalcopyrite are paragenetically early, and barite and amethystine quartz are paragenetically later (Tanton, 1931). Pitchblende (also known as uraninite) also occurs at the Enterprise and Dorion Amethyst deposits, which suggests a link to unconformity-related uranium-bearing deposits (Franklin and Mitchell, 1977; Scott, 1990).

Unconformity-Related Uranium-Bearing Veins

Unconformity-related uranium deposits occur in veins and vein breccias that occupy north-trending regional-scale faults and shear zones, as well as in lithologic pinchouts along the unconformity between Archean rocks and early Mesoproterozoic sandstone of the Sibley Group (Franklin, 1978; Smyk and Franklin, 2007). The Sibley Group is a ~950-m-thick sequence of relatively flat lying, siliciclastic and chemical sedimentary rocks (Rogala and others, 2007) that was deposited in a north-trending intercontinental basin between 1,537+10/-2 Ma (Davis and Sutcliffe, 1985) and 1,339±33 Ma (Franklin and others, 1980). Regional fault zones or onlap of the basal Sibley against Archean highs may have acted as stratigraphic traps for migrating hydrothermal fluids (Franklin, 1978). Ruzicka and LeCheminant (1984) obtained a date of 1,090±20 Ma for pitchblende and hematite mineralization in the Black Sturgeon Lake area in the Nipigon Embayment.

Copper Sulfide-Bearing Veins

Four vertical veins that carry chalcocite-bearing calcite stringers with trace amounts of chalcopyrite and silver occur in flat-lying amygdaloidal basalt flows of the Plateau Stage Osler Volcanics. Veins similar to those in the Mainland Group in Ontario continue into northeastern Minnesota (Grout and Schwartz, 1933). In this part of Minnesota, the geology consists of flat-lying rocks of the Rove Formation intruded by Logan sills, which are cut off to the south by younger rocks of Plateau Stage Duluth Complex intrusions and overlying reversed-magnetic-polarity volcanic rocks. Veins described by Grout and Schwartz (1933) include calcite veins, calcite-barite veins, calcite-sulfide veins, and calcite-barite-sulfide veins; silver was not reported. Most of these veins were of insufficient size and economic importance to be included in the USGS MRDS database. An exception is a small copper sulfide vein with chalcopyrite, bornite, chalcocite, and pyrite in calcite gangue that cuts a Rift Stage diabase dike and Rove Formation argillite on Susie Island off the Lake Superior shoreline (Schwartz, 1928).

Timing of Thunder Bay Vein Mineralization

The diverse group of mineralized veins in the Thunder Bay area differs in setting, metal assemblages, and gangue contents, but these veins presumably relate to a single, extended hydrothermal event with metal assemblages that indicate varying metal sources (Smyk and Franklin, 2007). The heat source driving the regional hydrothermal system on the north side of the MRS was not Plateau Stage sill intrusions or Rift Stage diabase dikes, as these would not have had enough heat to reach the high fluid inclusion temperatures reported by Kissin and Jennings (1987). There is evidence, however, of possibly contemporaneous regional intrusive events. The Moss Lake intrusion that cuts the reversed-magnetic-polarity Osler Volcanics has a baddeleyite date of 1,094.7±3.1 Ma (Heaman and others, 2007). A small group of zircons from gabbro near the margin of the St. Ignace Island Complex, which also intrudes the upper section of the Osler Volcanics, was dated at 1,089±3.2 Ma (Smyk and others, 2006). These are within error of the 1,090±20 Ma date obtained from pitchblende mineralization (Ruzicka and LeCheminant, 1984), which suggests that the magmatic heat of intrusion related to local late Rift Stage or Late-Rift Stage magmatism could have driven the hydrothermal system that created the diverse vein mineralization in the Thunder Bay area.

Sediment-Hosted Stratiform Copper

Sediment-hosted stratiform copper deposits are located on the south shore of Lake Superior, near the Porcupine Mountains of Michigan. Economic mineralization is fine-grained disseminated chalcocite restricted to the lower 1 to 4 m of shale and siltstone in the Nonesuch Formation (Mauk and others, 1992). The two principal stratiform copper deposits are Copperwood, located within the Western syncline (a N. 60° W.-plunging open fold southwest of the Porcupine Mountains), and White Pine, located to the northeast of the Porcupine Mountains.

Primary mineralization at both Copperwood and White Pine is attributed to chalcocite replacement of pyrite during diagenesis by compaction-driven, Cu-rich hydrothermal fluids moving upward through underlying Copper Harbor Formation red beds and into pyrite-bearing gray and black shale of the lower Nonesuch Formation (Ensign and others, 1968; Mauk and others, 1992; Swenson and others, 2004; Bornhorst and Williams, 2013). Copper in the mineralizing fluid was leached from volcanic clasts in the underlying immature Copper Harbor Formation; compaction from deposition of the overlying 4 km of Freda Formation created a single-pass mineralizing event of the lower Nonesuch (Swenson and others, 2004).

Mineralization at the White Pine deposit is interpreted to have occurred during late diagenesis of the Nonesuch Formation (Ensign and others, 1968; Mauk and others, 1992), perhaps several millions of years following sediment deposition. Based on reported ages of Nonesuch Formation deposition (1,081±9 Ma, Ohr, 1993; 1,078±24 Ma, Cumming and others, 2013), mineralization of these sediment-hosted stratiform copper deposits falls within the MRS Post-Rift Stage. The reported timing of Nonesuch diagenesis and a date of 1,090±20 Ma for pitchblende in a Thunder Bay area uranium unconformity vein overlap. If the diverse vein mineralization in the Thunder Bay region was driven by Late-Rift Stage magmatic heat, however, it is probable that the formation of the multiple mineralized veins in Ontario pre-dates the stratiform copper mineralizing event in Michigan. This assumption is supported by the relative timing of the change of the MRS from a primarily magmatic regime to a primarily sedimentary regime.

Compressional Stage Characteristics

Thrusting and inversion in parts of the MRS are attributed to the renewal of northwest-directed compression caused by a phase of the Grenville Orogeny to the east (Cannon, 1994). This is the Compressional Stage of the MRS that created the geometry of older basalts thrust over younger sediments along reverse faults, which is seen today in the Lake Superior region. Faulting occurred around 1,060±20 Ma (Cannon and others, 1993), as indicated by thermal resetting of Rb-Sr biotite ages in the upper plate of a listric fault system in Michigan and Wisconsin that is part of the series of reversed normal faults that bound central rift basins.

Compressional Stage Hydrothermal Mineral Deposits

Native Copper±Native Silver in Basalt and Interflow Sedimentary Rocks

Native copper accompanied by minor native silver mineralization is the most famous of all MRS mineral deposits. Native copper showings and occurrences are ubiquitous in exposed normal-magnetic-polarity Rift Stage basalts, although economic deposits are found only in Michigan’s western Upper Peninsula. Comprehensive descriptions of native copper mineralization are given in Butler and Burbank (1929), Broderick and others (1946), White (1968), and Bornhorst (1997).

Native copper and native silver are the only ore minerals in this deposit type. Copper and silver occur predominantly as native metals rather than in sulfide minerals because Cu-bearing metamorphic fluids were derived from deeply-buried subaerial basalts that had degassed most volatiles, including sulfur, during eruption (Cornwall, 1956; White, 1968). Native copper ore bodies are mostly stratiform deposits, locally called “lodes,” and are found in amygdaloidal basalt flow tops—which are often fragmental or rubbly—or within interflow conglomerate beds. Some steeply dipping veins, locally called “fissure veins,” that cross-cut layered basalt flows also carry native copper (White, 1968).

Native copper mineralization is epigenetic, with both copper and mineralizing fluid thought to have originated from the thick buried basalt sections within the central rift axis in Lake Superior (Stoiber and Davidson, 1959; White, 1968; Jolly, 1974; Bornhorst, 1997). Precipitation of native copper may have been caused by mixing with cooler, dilute meteoric water (Livnat, 1983; Bornhorst, 1997) that was accompanied by reactions between mineralizing fluid and rock that resulted in the removal of iron in the immediate vicinity of copper, thus causing a bleaching effect (Butler and Burbank, 1929). Brecciated and recemented vein-filling minerals suggest that mineralization was contemporaneous with faulting and minor folding of the Rift Stage basalts during the Compressional Stage (White, 1968). Bornhorst and others (1988) dated amygdule-filling potassium felspar, calcite, epidote, and chlorite using Rb-Sr techniques to constrain the timing of native copper mineralization as between 1,060 and 1,047 Ma (± ~20 Ma). Thus, the timing of native copper mineralization is some 30 to 40 million years after eruption of the host basalt section.

Despite the common occurrence of native copper showings around Lake Superior, 97 percent of the total native copper production came from only 10 lode deposits located within a small 45-km by 5-km section of Rift Stage PLV along the Keweenaw Peninsula of Michigan. One lode deposit, the Calumet and Hecla Conglomerate, accounted for nearly 40 percent of the production from that section (White, 1968).

Second-Stage Native Silver±Native Copper

A “second-stage” mineralizing episode at the White Pine deposit—which locally increased the grade of the initial “main-stage” (Post-Rift Stage) sediment-hosted stratiform copper mineralization—is temporally related to the much larger native copper mineralization event of the Compressional Stage (Mauk and others, 1992). During regional faulting related to the Grenville Orogeny compression, copper-bearing fluids moved along multiple strike-slip and thrust faults that cut the White Pine mine. Ruiz and others (1984) analyzed calcites in late veins that cut the chalcocite mineralization at the White Pine mine and obtained a Rb-Sr date of 1,047±35 Ma for second-stage mineralization. The abundance of silver in sandstone at the contact between the Copper Harbor and Nonesuch Formations created a short silver boom from 1872 and 1876 that saw the opening of a number of small silver mines and a stamp mill (Rominger, 1876; White and Wright, 1954).

Chalcocite in Basalt

Chalcocite is widespread in trace amounts throughout much of the Keweenaw Peninsula, especially in fissures cutting basalt (Butler and Burbank, 1929). Within the lower section of the PLV, however, near the northeast tip of the peninsula, there are seven chalcocite deposits and all but one are hosted by basalt. The deposits are restricted to an area 2 km by 13 km that is stratigraphically below the Bohemia Conglomerate, a prominent interflow sedimentary layer just above the Keweenaw fault that can be traced along strike for more than 100 km.

There is no spatial overlap between economic native copper mineralization and the chalcocite mineralized area, although there are similarities between the two. Alteration minerals related to chalcocite include epidote, quartz, hematite, pumpellyite, chlorite, albite, potassium feldspar, and laumontite, which matches the minerals found with native copper (Robertson, 1975). Both native copper and chalcocite are most abundant in fragmental basalt flow tops. The major difference between the two, other than native metal versus sulfide, is the presence of the dikes and the high degree of fault-related fracturing that controlled the distribution of sulfide mineralization within the chalcocite zone. It is likely that the same hydrothermal event that resulted in the deposition of native copper higher in the PLV section also deposited chalcocite in this limited area.

Unconformity-Related Uranium Veins

Unconformity-related uranium veins occur along sheared contact zones between MRS diabase dikes and an Archean gneissic tonalite suite in the Theano Point-Montreal River area along the eastern shore of Lake Superior, Ontario. Pitchblende occurs with hematite in gangue calcite veins along the contact between diabase and Archean rocks, as well as in tension cracks in diabase; pyrite as well as lead and copper selenides are also found in some of the veins (Robertson and Gould, 1983). The uranium source is the Archean gneiss, which is known to be locally radioactive (Grunsky, 1991). The timing of mineralization is unknown, although the steep northerly dip of the dikes and shearing along their margins suggest that mineralization could be related to hydrothermal activity concurrent with faulting during the Compressional Stage.

Summary

The MRS in the Lake Superior region is a diverse suite of rocks which have been categorized into different stages of tectonic activity and rift development, each having characteristic host rocks, metal endowments, and mineral deposit types (fig. 2). Development of the MRS began with magmatic activity of the Plateau Stage and the Rift Stage, which were then followed by minor magmatic activity of the Late-Rift Stage. During a Post-Rift Stage, clastic sediments were deposited into thermally subsiding basins. A final compressional event (the Compressional Stage) reversed motion along originally normal faults as clastic sedimentation continued. Each stage of the rift evolution is characterized by specific ore deposit types that are largely confined both by their physical location in rift rocks and by the type and timing of mineralization. Controlling factors for magmatic deposits include sulfur sources, magma compositions, and magmatic propagation styles. For hydrothermal deposits, fluid compositions, favorable structures controlling fluid flow, and the controls on mineral precipitation all contributed to metal endowment and richness. We present a database (table 1) of known MRS deposits taken from public deposit databases (categorized by deposit type and stages of rift development). This database has resulted in a space and time framework for MRS mineralization events.

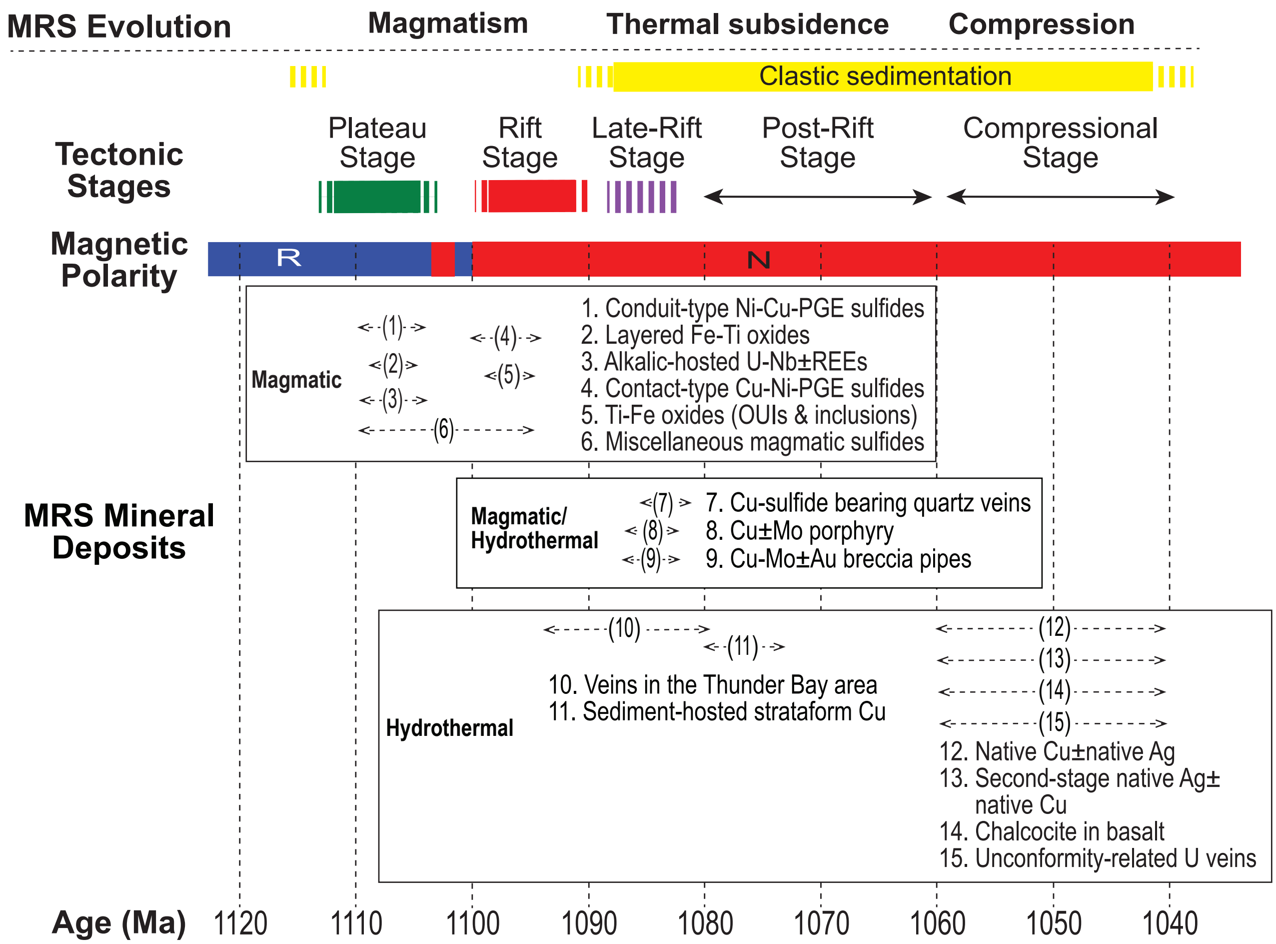

Figure 2. Summary of the tectonic and mineralization history of the Midcontinent Rift System (MRS). In the “Tectonic Stages” section, colored boxes and bars represent the timing of rock emplacement and deposition for the corresponding stages; arrows represent the estimated timing of the Post-Rift Stage and the Compressional Stage. Magnetic polarity is indicated by blue for reversed (R) and red for normal (N) magnetic polarity. For MRS mineral deposits, numbers refer to the name of the deposit type (given within the corresponding box) and dashed arrows represent the assumed duration of mineralization. Timing of mineralization is estimated from the age of host rocks and (or) timing of mineralization, where known. Abbreviations: Ag, silver; Au, gold; Cu, copper; Fe, iron; Ma, mega-annum; Mo, molybdenum; MRS, Midcontinent Rift System; N, normal magnetic polarity; Nb, niobium; Ni, nickel; OUIs, oxide-ultramafic intrusions; PGE, platinum-group element; R, reverse magnetic polarity; REEs, rare earth elements; Ti, titanium; U, uranium.

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Appendix 1

Tables 1.1 and 1.2 give definitions for the mineral deposit categories (column G) in the database (table 1; available as a separate file at https://doi.org/10.3133/ofr20201069). Deposits located in Ontario, Canada, correspond to the definitions in table 1.1 and deposits located in the United States correspond to the definitions in table 1.2.

Table 1.1. Definitions for mineral deposit categories (column G) in the database (table 1) for deposits located in Ontario, Canada.

[The mineral deposit categories and definitions are those listed in the Ontario Geological Survey (OGS) Mineral Deposit Inventory (MDI; Ontario Ministry of Energy, Northern Development and Mines, 2019). They were obtained from appendix 3 of Wilson and others (2008)]

Mineral Deposit Category	Definition
Discretionary Occurrence	An occurrence or deposit that does not meet any of the defined criteria but is entered into the MDI database based upon a subjective decision by a MNDM [Ontario Ministry of Energy, Northern Development and Mines] geologist.
Occurrence	Mineralization is present in 2 dimensions as indicated by surface rock sampling (channel or grab) and (or) isolated diamond drill intersection(s). At least one sample must meet the minimum requirements for a mineral occurrence.
Prospect	Mineralization is present in 3 dimensions, indicated by diamond drilled intersections ± surface rock sampling. Mineralization occurs for significant distances along strike and down dip with a minimum of 3 intersections that meet the minimum requirements for a prospect.
Developed Prospect with Reserves	Mineralization is present and defined in 3 dimensions as outlined by a delineation diamond drill program. Mineralization occurs for significant distances along strike and down dip with multiple intersections that meet the minimum requirements for a Prospect. Reserves must meet the minimum requirements for a producing mine, a past-producing mine, or a developed prospect with reserves.
Developed Prospect without Reserves	Mineralization is present in 3 dimensions as outlined by a delineation diamond drill program. Mineralization occurs for significant distances along strike and down dip with numerous intersections that meet the minimum requirements for a Prospect. Reserves figures have not been published or do not meet the minimum requirements for a producing mine, a past-producing mine or a developed prospect with reserves.
Past Producing Mine	Commodities were in the past extracted for sale. No defined in-situ reserves. Past production must have met the minimum requirements for a producing mine, a past-producing mine or a developed prospect with reserves.
Past Producing Mine with Reserves	Commodities were in the past extracted for sale. Total past production plus in-situ reserves must meet the minimum requirements for a producing mine, a past-producing mine or a developed prospect with reserves.
Producing Mine	Commodities are currently extracted for sale. Total of the commodity produced plus the published defined ore reserves must meet the minimum requirements for a producing mine, a past-producing mine or a developed prospect with reserves.

Table 1.2. Definitions for mineral deposit categories (column G) in the database (table 1) for deposits located in the United States

[The mineral deposit categories and definitions are those listed in metadata for the U.S. Geological Survey Mineral Resources Data System (MRDS; Schweitzer, 2017)]

Mineral Deposit Category	Definition
Occurrence	Ore mineralization in outcrop, shallow pit or pits, or isolated drill hole. Grade, tonnage, and extent of mineralization essentially unknown. No production has taken place and there has been no or little activity since discovery with the possible exception of routine claim maintenance.
Prospect	A deposit that has gone beyond the occurrence stage. This is subsequent work such as surface trenching, adits, or shafts, drill holes, extensive geophysics, geochemistry, and (or) geologic mapping has been carried out. Enough work has been done to at least estimate grade and tonnage. The deposits may or may not have undergone feasibility studies that would lead to a decision on going into production.
Producer	A mine in production at the time the data was entered. An intermittent producer that produces on demand or seasonally with variable lengths of inactivity is considered a producer.
Past Producer	A mine formerly operating that has closed, where the equipment or structures may have been removed or abandoned.
Unknown	At the time of data entry, either the development status was unknown or the data source this record came from did not specify this value.

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