FIELD GUIDE TO THE COPPER-NICKEL-PLATINUM GROUP ELEMENT DEPOSITS OF THE LAKE SUPERIOR REGION

Presented as part of

Workshop on the Copper-Nickel-Platinum Group Element Deposits of the Lake Superior Region

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Field Guide to the
Copper-Nickel-Platinum Group Element Deposits
of the Lake Superior Region

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Recommended Citation Format


Workshop Organizers
Frontpiece: Mesoproterozoic geology of the Lake Superior region. Cu-Ni-PGE deposit to be visited during the five field trip days are tagged.
Contributing Corporate Partners

Kenscott Exploration
Rio Tinto
Lundin Mining
DM Duluth Metals
TWIN Metals Minnesota
Orvana Minerals Corp.
North American Palladium Ltd.
Panoramic Resources Ltd.
Stillwater Canada Inc.
Teck
Polymet Mining
Golder Associates
Introduction

For over a century, many geologic, geochemical, geochronologic, and geophysical studies have been focused on the Mesoproterozoic (1.1 Ga) volcanic, intrusive, and sedimentary rocks that compose the Midcontinent Rift (MCR) in the Lake Superior region. In the past quarter century, in particular, the empirical data collected from such studies have vastly improved our understanding of the three-dimensional structure and tectono-magmatic evolution of the MCR. These studies have shown the Midcontinent Rift to be one of the best preserved large igneous provinces of Precambrian age. Moreover, research has suggested that the MCR was influenced, if not initiated, by a starting mantle plume.

The geologic understanding of the MCR, which is well exposed in the Lake Superior region, is continuing to improve due to a steady commitment to bedrock geologic mapping principally conducted by the Minnesota Geological Survey (e.g., Jirsa et al., 2011), the Ontario Geological Survey (e.g., Hart and MacDonald, 2007), and the U.S. Geological Survey (e.g., Nicholson et al., 2004). These three entities are currently collaborating on compiling a digital geologic map of the MCR that will include related tables of geochemical and geochronologic data and mineral deposit information (Nicholson et al., in preparation).

An understanding of the deeper structure of the rift and interpretations of its tectonomagmatic evolution have benefited from numerous interpretive studies of geochemical, geochronologic and geophysical data collected on the rift. These data sets and some of the more notable studies include:

1) High-resolution aeromagnetic data and a dense array of gravity measurements (Chandler et al., 1989; Chandler, 1990; Thomas and Teskey, 1994; Allen et al., 1997; Daniels and Snyder, 2002; Chandler and Lively, 2007);

2) Deep-crustal seismic reflection profiles (Behrendt et al., 1988; Chandler et al., 1989; Cannon et al., 1989; Hinze et al., 1990; McGinnis and Mudrey, 1991; Hinze et al., 1992; also see papers in 1994 Special Issue of Canadian Journal of Science v. 21, no. 4);

3) Geochemical and radioisotopic analyses of MCR igneous rocks (BVSP, 1981; Brannon, 1984; Green, 1986; Green et al., 1987; Sutcliffe, 1987; Paces and Bell, 1989; Nicholson and Shirey, 1990; Miller and Weiblen, 1990; Klewin and Berg, 1990, 1991; Lightfoot et al., 1991; Shirey et al., 1994; Miller and Ripley, 1996; Shirey, 1997; Miller and Chandler, 1997; Nicholson et al., 1997; Wirth et al., 1997; Vervoort and Green, 1997; Vervoort et al., 2007; Hollings et al., 2007a, b & c; Rogala et al., 2007; Hollings et al., 2010, 2012);

4) High precision U-Pb dates of volcanic and intrusive rocks (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 et al., 1997; Vervoort et al., 2007; Heaman et al., 2007; Hoaglund, 2010); and

The MCR hosts several types of world-class ore deposits that have been exploited for many centuries. It is well established that nomadic Paleo-Indians mined native copper deposits on the Keweenaw Peninsula and Isle Royale as far back as 5,000 years ago (Martin, 1995). The first mineral rush in the United States was triggered by an 1841 report of mineable quantities of native copper in MCR basalt flows on the Keweenaw Peninsula by Michigan State Geologist Douglas Houghton. Although native copper (and minor silver) mining ended in 1967 and related copper sulfide mining at White Pine near Ontonagon, Michigan ended in 1996, increased global demand for base and precious metals over the past decade has spurred a historic surge in the exploration of various ore deposit types associated with the MCR, with several properties set to begin mining soon.

Chief among the deposit types being considered for mining is the low grade Cu-Ni-PGE sulfide ore occurring along the base of the Duluth Complex in northeastern Minnesota. Intermittent exploration of these deposits since their discovery in the early 1950’s has proved out the largest undeveloped resource of copper on Earth (Eckstrand and Hulbert, 2007). Stepped up exploration activity over the past decade has brought several projects to the pre-feasibility and environmental permitting stages with mining anticipated to commence over the next several years. Similar Cu-Ni-PGE deposits associated with the Coldwell Complex near Marathon, Ontario are also in the pre-feasibility stage of development.

In 2002, the discovery of massive Ni-Cu-PGE sulfide in the Eagle deposit near Marquette, Michigan stimulated a new round of exploration activity focused on the search for small MCR-related ultramafic intrusions emplaced into sulfidic sedimentary rocks. Currently, this search has identified over a half-dozen related Ni-Cu-PGE prospects in the Lake Superior region, with the Eagle deposit already permitted to begin mining in 2013. The recent discovery of numerous ultramafic intrusions associated with the early stages of the MCR has prompted active petrologic research on these bodies (Heggie, 2005; Laarman, 2007; Hollings et al, 2007b; Ding et al., 2010; Goldner, 2011; Foley, 2011;) and a reevaluation of the tectono-magmatic evolution of the rift (Heaman et al., 2007; Hollings et al., in press).

In the first part of this overview, we review the geology, structure, and igneous chemostratigraphy of the MCR, and present some current ideas about its tectono-magmatic evolution. In the second part, we summarize the salient characteristics of the various ore deposits types associated with the MCR in the Lake Superior region.

Geologic Setting of the Midcontinent Rift

Although buried by younger Phanerozoic sediments over most of its 2500 kilometer length, the arcuate, segmented path of the MCR is easily traceable along gravity and magnetic anomalies that project in two arms, southwest and southeast, of exposures in the Lake Superior region (Fig. 1). The intense gravity and aeromagnetic anomaly formed by the MCR is one of the most distinctive geophysical features of the North American continent (King and Zietz, 1971; Hinze et al., 1992). Bouger gravity anomalies associated with the MCR range from a positive anomaly of over 60 mgals over the eastern part of the Duluth Complex to less than -90 mgals on the eastern flank of the rift in western Wisconsin (Allen et al., 1997).

Along the southwestern arm, the rift crosses geologic provinces ranging in age from 2.8 Ga to 1.7 Ga (Van Schmus, 1992; Holm et al., 2007; Fig. 2). In the Lake Superior region, the rift cuts across Late Archean (2.8-2.6 Ga) granite-greenstone terranes of the southern Superior province. From Lake Superior south into Iowa the rift crosses several terranes within the Paleoproterozoic (1.85 Ga) Penokean Orogen. The northern part of the orogen is composed of sedimentary rocks deposited at the continental margin of the Superior craton: these sedimentary rocks display increased deformation and metamorphism to the south (Cratonic Margin Domain, Fig. 2). South of the Niagara fault zone, a major suture zone, the orogen
consists of an island arc assemblage of volcanic, intrusive, and immature sedimentary rocks (Pembine-Wausau Terrane, Fig. 2), as well as a block of isotopically reset Archean rocks, including gneiss dated at 3.6 Ga (Marshfield Terrane, Fig. 2). South of another major suture zone, the Spirit Lake Tectonic Zone (Fig. 2), which is largely inferred from geophysical and isotopic data, the MCR cuts across the Yavapai Province, a 1.7 Ga accreted terrane composed dominantly of felsic igneous rocks. Metamorphism, deformation, plutonism, and gneissic doming associated with the Yavapai orogeny overprint much of the Penokean as far north as the southern shore of Lake Superior (Fig. 2).

Figure 1. Geophysical characteristics of the southwest arm of the Midcontinent Rift in the north-central United States. A) Bouger gravity anomaly map (dotted lines indicate buried crustal blocks inferred from gravity data (Kucks, 1999); see Fig. 3). B) Shaded-relief map of the total magnetic intensity anomaly (Bankey et al., 2002).

The eastern arm of the MCR is deeply buried beneath Paleozoic rocks of the Michigan basin and has been encountered in only a few deep drill holes (Brown et al., 1982). The gravity and magnetic signature of the MCR ends abruptly where as it crosses the geophysical trace of the Grenville front in southeastern Michigan at nearly a right angle. The Grenville front is a tectonic boundary marking the northwestern limit of penetrative deformation and metamorphic effects produced by the Elzevirian (1240 to 1160 Ma) and Ottawan orogenies (1090 to 1025 Ma), which together created the Grenville province (Easton, 1992). These two orogenies bracket the period of igneous activity and rifting of the MCR (1115-1086 Ma; Heaman et al., 2007). Cannon (1994) has suggested that rifting of the Midcontinent occurred during a period of diminished compression within the Grenville province whereas late tectonic inversion of the rift resulted from renewed tectonism (compression) during the Ottawan orogenic phase.

Structure of the Midcontinent Rift

Extensive bedrock mapping of the MCR in the Lake Superior basin has provided a robust picture of the present-day exposure of rift-related rocks (Fig. 3). This shows the rift to be composed of three major lithologic components: 1) a thick edifice of subaerial lava flows, 2) local concentrations of plutonic to hypabyssal intrusive rocks, and 3) an upper sequence of sedimentary rocks (Bayfield and Oronto Groups). More localized units occurring within pre-rift basement rocks include generally rift-parallel dike swarms, small ultramafic intrusions, and small alkaline and carbonatite intrusions. Also shown on Figure 3 of major faults that commonly juxtapose volcanic and sedimentary rocks.
When the surface features are integrated with the wealth of regional geophysical data collected over the MCR, especially the seismic reflection profiles collected across Lake Superior in 1986 for the GLIMPCE project (Great Lake International Multidisciplinary Program on Crustal Evolution; Behrendt et al., 1988), the result reveals the full, three-dimensional structure of the MCR. Seismic profiles across Lake Superior combined with Bouger gravity data indicate that the deepest part of the MCR lies beneath western Lake Superior, where the rift fill is as much as 36 km thick and where volcanic rocks comprise about two-thirds of the total (Cannon et al., 1989; Trehu et al., 1991; Hinze et al., 1992; Thomas and Teskey, 1994; Allen et al., 1997; Fig. 4). A minimum estimate for the volume of mafic rock in the Lake Superior region is $1.3 \times 10^6$ km$^3$ (Hutchinson et al, 1990), whereas Cannon (1992) suggest a more realistic estimate is over $2 \times 10^6$ km$^3$. This volume is comparable to many post-Mesozoic, continental-based, large igneous provinces (LIPs) (Table 1).
Figure 3. Midcontinent Rift geology in the Lake Superior region. Major volcanic and intrusive units are labeled. Dashed lines denote major faults that served as graben-bounding normal faults during the magmatic phase of rifting, but were reactivated to reversed offset during late compression: KF-Keweenaw Fault, IRF-Isle Royale Fault, DF-Douglas Fault. Red line denotes GLIMPCE Line A - the seismic reflection profile used for the geologic crustal model shown in Figure 4.
These geophysical data also suggest that a volume of magma nearly equivalent to that filling the rift, underplated the crust such that complete crustal separation probably occurred at least in the western Lake Superior area (e.g., Fig. 4; Behrendt et al., 1988; Trehu et al., 1991; Hinze et al., 1992; Allen et al., 1997). This at least doubles the amount of magmatic fill, as observed in other LIPs such as the Karoo-Ferrar igneous province associated with the rifting of Antarctica from southern Africa (fill = 5x10^6 km^3, fill + underplate = 10x10^6 km^3, Ernst and Buchan, 2001). Considering the rift fill, the volume of underplated material, and the unknown amount of eroded material, the Midcontinent Rift clearly is a world-class large igneous province.

Removing the effects of the late compression, the extensional structures of the rift also reveal themselves to be complex. Geophysical models across the MCR in the western Lake Superior region and along its southwestern arm, suggest that it was composed of a series of en echelon asymmetric grabens that change their polarity across subtle to well-defined accommodation zones (Chandler et al., 1989; Cannon et al., 1989; Dickas and Mudrey, 1997; Anderson, 1997; Berendsen, 1997). The trans-rift Thiel fault in central Lake Superior (Fig. 3) is an example of such an accommodation zone. Most of the volcanic rocks of the rift are confined within large-scale reversed faults that have inverted the grabens into horst structures (e.g., Keweenaw, Douglas, and Isle Royale faults, Fig. 3). Whereas 10 to 20 kilometers of volcanic rocks commonly are contained within the graben/horst structures, lava accumulations outside the bounding faults rarely exceed 5 kilometers (e.g., Fig. 4). This indicates that the reverse faults must have originally acted as normal growth faults and perhaps magma conduits to rapidly subsided and in-filled axial grabens (Cannon, 1992). Moreover, whereas volcanic rocks outside the central graben are predominantly older lava accumulations of reversed paleomagnetic polarity, younger normal polarity lavas comprise most of the exposed volcanic sequences within the grabens in the western part of the MCR (Figs. 3 & 4). This implies that graben formation began some time after the initiation of volcanic activity (Cannon et al., 1989). Interestingly, beneath the eastern part of the Lake Superior basin, where the axial graben is not bounded by distinct normal faults as in the west, older reversed polarity lavas are interpreted to comprise most of the 15-kilometer-thick volcanic sequence (Mariano and Hinze, 1994).

In western Lake Superior, the rift structure is further complicated by the effects of large, crustal blocks isolated within the volcanic basins (Fig. 3). Integrated modeling of gravity, magnetic, and seismic data over western Lake Superior (Sexton and Henson, 1994; Allen et al., 1997) has identified two areas within the axial part of the rift where the volcanic section pinches out. These areas are presumed to be large blocks or ridges of granitic crust, called the Grand Marias block and White's ridge (Figs. 1A & 3). These blocks may represent detached pieces of crust that became isolated during crustal separation. During volcanism, they stood as structural highs and exerted significant control on the shape of the graben in which the lavas accumulated, particularly the Portage Lake Volcanics (PLV). Allen et al. (1997) demonstrated that the axis of the central rift basin is centered between the Keweenaw Peninsula and Isle Royale and then curves around the Grand Marais block to the northwest toward the Minnesota coast. Miller and Chandler (1997) have suggested that the western growth fault margin of the PLV-equivalent rocks in Minnesota corresponds to the Finland Tectonomagmatic Discontinuity (FTMD) - an extensive arcuate dike and sill complex that is part of the hypabyssal Beaver Bay Complex (Fig., 3). White's Ridge further divides the western Lake Superior from another deep trough of volcanics to the southwest (Fig. 3).
Figure 4. Geologic crustal model across the central part of Lake Superior based on seismic reflection data along GLIMPCE Line A (shown in Figure 3) and Bouger gravity data (after Trehu et al., 1991 and Thomas and Teskey, 1994). IR and KF denote the Isle Royale and Keweenaw Faults, respectively. High density lower crust is interpreted to be mafic underplated material.

The Duluth Complex and related intrusions in northeastern Minnesota (Fig. 3) also cause the MCR to deviate from a linear graben form. Modeling of Bouguer gravity data over the Duluth Complex, which is characterized by two broad highs of greater than 50 mgals (Fig. 1A), indicates that the complex extends to a depth of about 13 km (Allen et al., 1997). The saddle between the two gravity highs has been attributed to another granitic crustal ridge, the Schroeder-Forest Center Ridge (SFC, Fig. 3; Miller and Chandler, 1997; Peterson and Severson, 2002), which divides the complex into two intrusive "basins". Although centered off the main axis of the rift, this accumulated thickness of magma is more than half of that which ponded in the central rift graben. Modeling of gravity data at the northern apex of Lake Superior by Thomas and Teskey (1994) suggest that a large mafic igneous complex with a thickness of as much as 20 km lies buried beneath the base of the Osler Group (Fig. 4). The reason that such large volumes of mafic magma ponded along the northwestern margin of the MCR is unclear but may be related to structural features of the pre-Keweenawan basement (Fig. 2). The Duluth Complex lies near the projection of the Penokean tectonic front and the Great Lakes tectonic zone (an Archean suture zone), along the projection of major Archean fault zones such as the Vermilion fault, and at the northern shelf margin of the Early Proterozoic Animikie basin. More specifically, sheet-like intrusions of the Duluth Complex and related bodies in Ontario appear to have been emplaced along the nearly concordant interface of subhorizontal Early Proterozoic sedimentary rocks of the Animikie Group and lava flows within the Keweenawan Supergroup.
Volcanic Sequences of the Midcontinent Rift

Stratified volcanic and sedimentary rocks contained within the MCR are collectively known as the Keweenawan Supergroup (Morey and Green, 1982). Although faulting and burial of thickened portions of the rift fill beneath Lake Superior preclude studies of a continuous and complete sequence of the rift stratigraphy, its main components may be pieced together from exposures around the Lake Superior basin (Fig. 3). Physical and lithologic attributes of the main volcanic and sedimentary sequences exposed around the Lake Superior basin are summarized in Table 1. A proposed chronostratigraphic correlation of the main volcanic sequences and bounding sedimentary units are shown in Figure 5. This compilation is a modest revision of the most recent correlation proposed by Hollings et al., 2007b, which is slightly modified from Nicholson et al. (1997).

Prior to 1985, the principal means of correlating MCR volcanic sequences in the Lake Superior region was by their magnetic polarity. In the western Lake Superior basin, most volcanic rocks were correlated relative to a single magnetic polarity reversal from early reversed to late normal (Figs. 3, 4 and 5). However, at Mamainse Point in eastern Lake Superior, an additional normal and reversed interval was noted (Annels, 1973; Klewin and Berg, 1990). In the past two decades, high-resolution U-Pb geochronologic studies of zircons and badellyites have replaced magnetic polarity as the main correlation tool for the volcanic and intrusive rocks of the MCR and have proven to be very important in the rapid expansion of our current knowledge of the rift. The age of the major R-N reversal is now constrained to have occurred between 1105 and 1102 Ma based on U-Pb ages for the uppermost reversely polarized lava in the Osler Volcanic Group, the Agate Point rhyolite (1105.3±2.1 Ma, Davis and Green, 1997) and the oldest normally polarized age for the granitic rocks of the Mellen Complex (1102±2 Ma, Zartman et al., 1997). Until very recently, no dateable material had been found in the Mamainse Point sequence, despite several attempts. Therefore, attempts to correlate its seemingly more complete volcanic package (based on extra polarity reversals) with western volcanic sequences had to rely on gross magnetic polarity and geochemical attributes (Nicholson et al., 1997; Shirey et al., 1994). However, an as yet unpublished, high precision U-Pb zircon age on a volcanic tuff at the top of the uppermost reversed polarity sequence, just below the Great Conglomerate, is reported to peg the top of the reversed sequence at around 1100 Ma (Hysell-Swanson, personal comm., May 2012).

One of the more distinctive attributes of the MCR compared to other mantle plume-influenced, large igneous provinces, is the prolonged period of magmatism - almost 30 million years. The current collection of over 80 high precision U-Pb ages indicate that magmatic activity that can be geochemically linked to the development of the MCR occurred between 1115 Ma and 1086 Ma (Fig. 5). Heaman et al. (2007) suggested that intrusions in northwestern Ontario emplaced between 1150 and 1130 Ma may also be related to the MCR, but adding these diverse compositions to the MCR magmatic episode more than doubles the duration of MCR magmatism and complicates the generally coherent picture of its geochemical evolution (Nicholson et al., 1997).

The MCR volcanic sequences are composed of predominantly subaerially-erupted, tholeiitic flood basalts, but also include intermediate and felsic flows and fluvial interflow sedimentary rocks (Green, 1982). The lithostratigraphy of the main volcanic sequences are schematically portrayed in Figure 5 with volcanic intervals being subdivided into dominantly primitive basalts (mg#s >50), dominantly evolved basalts to basaltic andesites (mg#s <50), mixed volcanics of diverse composition (basalt to rhyolite), and rhyolite flows. Although the lithostratigraphies of the main volcanic sequences are distinct from one another in detail, there is a surprising commonality in their general chemostratigraphy (Nicholson et al., 1997). Based on the correlations shown in Figure 5, generalized stratigraphic variations of select
lithochemical and isotopic compositions of mafic to intermediate lavas through the various volcanic packages are summarized in Figure 6.

Table 1: Attributes of Principal Volcanic and Sedimentary MCR Units in the Lake Superior Basin*

<table>
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<tr>
<th>Groups</th>
<th>Main Subdivisions (sequences and formations)</th>
<th>Exposed Thickness (m)</th>
<th>Polarity</th>
<th>Dominant Lithologies</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bayfield Group</td>
<td>Chequamegon Sandstone</td>
<td>150-300</td>
<td>N</td>
<td>Subarkosic sandstone</td>
<td>Morey, 1977</td>
</tr>
<tr>
<td></td>
<td>Hinckley/Devil Island/Jacobsville</td>
<td>90-150</td>
<td>N</td>
<td>Quartz sandstone, minor siltstone</td>
<td>Ojakangas &amp; Morey, 1982</td>
</tr>
<tr>
<td></td>
<td>Fond du Lac/Oreinta/Jacobsville</td>
<td>600-3000</td>
<td>N</td>
<td>Sublithic to subarkosic sandstone, minor siltstone, shale</td>
<td>Morey &amp; Van Schmus, 1988</td>
</tr>
<tr>
<td>Oronto Group</td>
<td>Freda Sandstone/Solor Church</td>
<td>350-1520</td>
<td>N</td>
<td>Arkosic sandstone, siltstone, microcement shale</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nonesuch Shale</td>
<td>75-230</td>
<td>N</td>
<td>Siltstone, shale &amp; sandstone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Copper Harbor Conglomerite</td>
<td>60-2100</td>
<td>N</td>
<td>Volcanoclastic conglomerate, lithic sandstone</td>
<td></td>
</tr>
<tr>
<td>North Shore Volcanic Group (MN)</td>
<td>Schroeder Lutsen basalts</td>
<td>400-900</td>
<td>N</td>
<td>Primitive basalts, rare Fe-basalt</td>
<td>Green, 1972</td>
</tr>
<tr>
<td></td>
<td>Upper northeast sequence</td>
<td>3700-3800</td>
<td>N</td>
<td>Mix of basalt &amp; rhyolite (&lt;40%), minor intermediate</td>
<td>Green, 2002</td>
</tr>
<tr>
<td></td>
<td>Lower northeast sequence</td>
<td>3000-3200</td>
<td>R</td>
<td>Primitive basalt-lower, variable basalt-upper</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Upper southwest sequence</td>
<td>8000-8500</td>
<td>N</td>
<td>Mostly basalt, minor intermediate &amp; rhyolite (&lt;10%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lower southwest sequence</td>
<td>&gt;370</td>
<td>R</td>
<td>Basalts, incomplete sequence cut by Duluth Complex</td>
<td></td>
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<td></td>
<td>Puckwunge-Napeming SS</td>
<td>10-60</td>
<td>R</td>
<td>Quartzose sandstone, siltstone, &amp; minor conglomerate</td>
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<td>Kallander Creek volcano - lower</td>
<td>~1500</td>
<td>R</td>
<td>Mostly basalts, minor andesite and rhyolite</td>
<td>Ojakangas &amp; Morey, 1982</td>
</tr>
<tr>
<td></td>
<td>Seimens Creek volcanics</td>
<td>1300-1500</td>
<td>R</td>
<td>Various basalts, locally Pys-Olphyricon basalt at base</td>
<td>Hubbard, 1975</td>
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<tr>
<td></td>
<td>Bessemer Quartzite</td>
<td>90</td>
<td>R</td>
<td>Quartzose sandstone, siltstone, and minor conglomerate</td>
<td>Nicholson et al., 1997</td>
</tr>
<tr>
<td>Portage Lake Volcanic Group (MI)</td>
<td>Lake Shore traps</td>
<td></td>
<td>N</td>
<td>Basaltic andesite to andesite</td>
<td>Nicholson et al., 1997</td>
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<td></td>
<td>Porcupine volcanics</td>
<td>&lt;4000</td>
<td>N</td>
<td>Mix of basalt, andesite and rhyolite</td>
<td>Paces &amp; Bell, 1989</td>
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<tr>
<td></td>
<td>Portage Lake volcanics</td>
<td>3000-5000</td>
<td>N</td>
<td>Mostly basalts with minor rhyolite and rare andesite</td>
<td></td>
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<tr>
<td>St. Croix Volcanic Gp (WI-MN)</td>
<td>Minong volcanics</td>
<td>?</td>
<td>N</td>
<td>Mostly basalts with minor rhyolite &amp; andesite near base</td>
<td>Nicholson et al., 2004</td>
</tr>
<tr>
<td></td>
<td>Chengwatara volcanics</td>
<td>?</td>
<td>N</td>
<td>Mix of basalt, basaltic andesite and andesite with minor rhyolite</td>
<td>Boerboom, 2002</td>
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<td>Main Subdivisions (sequences and formations)</td>
<td>Exposed Thickness (m)</td>
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<td>Osler Volcanic Group (ON)</td>
<td>Upper Suite</td>
<td>&lt;700</td>
<td>N/R</td>
<td>Basalts</td>
<td>Mellwaine &amp; Wallace, 1976</td>
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<td></td>
<td>Central Suite</td>
<td>&lt;1500</td>
<td>R</td>
<td>PI-phryic &amp; aphyric basalts capped by porph. rhyolite</td>
<td>Lightfoot et al., 1991</td>
</tr>
<tr>
<td></td>
<td>Lower Suite</td>
<td>&lt;800</td>
<td>R</td>
<td>Pyl: Ol-phryic basalts, basal rhyolite</td>
<td>Hollings et al., 2007</td>
</tr>
<tr>
<td></td>
<td>Simpson Island Formation</td>
<td>10-25</td>
<td>R</td>
<td>Polymict conglomerate and arkosic sandstone</td>
<td></td>
</tr>
<tr>
<td>Mamainse Point Volcanic Group (ON)</td>
<td>Units 6-8</td>
<td>~2000</td>
<td>N</td>
<td>Ophitic to intergranular basalts</td>
<td>Anzells, 1973</td>
</tr>
<tr>
<td></td>
<td>Unit 5</td>
<td>700</td>
<td>N</td>
<td>Variable basalts and basaltic andesites</td>
<td>Klevin and Berg, 1990</td>
</tr>
<tr>
<td></td>
<td>Units 3 &amp; 4</td>
<td>375</td>
<td>R</td>
<td>Mostly PI-phryic basalts (3), some Ol-phryic basalts (4)</td>
<td>Shirey et al., 1994</td>
</tr>
<tr>
<td></td>
<td>Unit 2</td>
<td>850</td>
<td>R</td>
<td>Ol- and Ol+PI-phryic basalts</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unit 1</td>
<td>250</td>
<td>R</td>
<td>Ol-phryic picritic basalts, one spilolite PI basalt flow</td>
<td></td>
</tr>
<tr>
<td>Michipicoten Island (ON)</td>
<td>Michipicoten Island Formation</td>
<td>~300</td>
<td>N</td>
<td>Andesite, transitional basalt, rhyolite, volcaniclastic</td>
<td>Anzells, 1974</td>
</tr>
</tbody>
</table>

* See Figure 3 for locations and Figure 5 for ages and correlations of most units
Figure 5. Chronostratigraphic correlation of the main volcanic sequences and bounding sedimentary units of the MCR in the Lake Superior basin. Also shown are main polarity intervals and U-Pb ages for volcanic and intrusive rocks (ages from 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 et al., 1997; Smyk et al., 2006; Vervoort et al., 2007; Heaman et al., 2007; Hoaglund, 2010; Ding et al., 2010; Goldner, 2011; Hollings et al., 2010; and Swanson-Hysell, pers. comm., 2012). Ages of intrusion are plotted to the left of volcanic sequence or pre-rift terranes into which they are intruded. Labels for some intrusion ages are: MC-Mellen Complex, E-Eagle, BBC-Beaver Bay Complex, DC-Duluth Complex, T-Tamarack, H-Hele, CC-Coldwell Complex, D-Disreali, JIS-Jackfish Lake Sill, S-Seagull, K-Kitto. Simplified lithostratigraphies of the four main volcanic-sedimentary packages are schematically portrayed; for details see the references listed in Table 1. The bold dashed lines indicate where the sequence is truncated by intrusions or major faults. Question marks indicate that the upper or lower age limit of the unit is unknown. Unit abbreviations for the Upper Michigan/NW Wisconsin package are: BSs-Bessemer Quartzite, SC-Siemens Creek Volcanics, LKC-Lower Kallander Creek Volcanics, UKC-Upper Kallander Creek Volcanics, PLV-Portage Lake Volcanics, SCV-St. Croix Volcanic Group, PM-Porcupine Volcanics, CHCg-Copper Harbor Conglomerate, LST-Lake Shore traps, NSh-Nonesuch Shale, and FSs-Freda Sandstone. For the North Shore Volcanic Group (NSVG) in northeastern Minnesota, which Green (2002) subdivides into two lithologically distinct, structural limbs, the unit abbreviations are: NSs-Nopeming Sandstone, PSs-Puckwunge Sandstone, LSW-Lower southwest sequence, LNE-Lower northeast sequence, USW-Upper southwest sequence, and UNE-Upper northeast sequence. The UNE and USW sequences are unconformably capped by the Schroeder-Lutsen sequence (SL). For the northwestern shore of Ontario (Black Bay Peninsula), the unit abbreviations are: SIF-Simpson Island formation, OVL-Osler Volcanic Group-lower suite, OLC-Osler Volcanic Group-central suite, and OLU-Osler Volcanic Group-upper suite. Upsection of the Osler Volcanics, southeast-dipping basalt flows on Isle Royale can be lithologically (and seismically) correlated with the northwest-dipping Portage Lake Volcanics (PLV) and overlying Copper Harbor Conglomerate (CHCg) exposed on the Keweenaw Peninsula (Fig. 3) and thus are given the same unit names (Huber, 1973). For volcanics of the Mamainse Point Volcanic Group exposed along the northeast Ontario shoreline, Klewin and Berg (1990) subdivide the sequence into 8 numbered intervals based on their lithologic and geochemical attributes. Several thick interflow volcanioclastic conglomerate units within the Mamainse Point section include: BCCg-basalt clast conglomerate, GCg-great conglomerate, and DCCg-Deadman’s Cove conglomerate. The Michipicoten Island Formation described by Annels (1974) is identified as MI.

Recognition that the frequency of eruption and the compositional characteristics of MCR magmatism was not constant has led many workers to subdivide the magmatic activity of the MCR into several stages (Sutcliffe, 1987; Shirey et al., 1994; Miller and Vervoort, 1996; Davis and Green, 1997; Nicholson et al., 1997; Vervoort et al., 2007; Heaman et al., 2007). Five magmatic stages are proposed in Figures 5 and 6 based on current geochronology, lithologic and geochemical data. The main attributes of these stages are as follows:

**Initiation Stage** (1115-1110 Ma) – this stage is represented by ultramafic to mafic intrusions that occur dominantly in the Thunder Bay-Lake Nipigon area of Ontario (Heaman et al., 2007) and by a buried intrusion in Michigan (Echo Lake gabbro: Cannon and Nicholson, 2001). No volcanics older than 1108±2 Ma have been dated in the MCR, though ages from the lowest parts of the volcanic sequences have yet to be acquired. Geochemical characteristics of picritic lavas of the lower parts of the Mamainse Point, PowderMill, North Shore, and Osler volcanic sequence are similar to estimated parent magmas of some early MCR ultramafic intrusions (Goldner, 2011; Foley, 2011), which may imply their being comagmatic and possibly contemporaneous. Given the thick sequence of reversed polarity lavas geophysically modeled in the eastern half of the Lake Superior basin (Mariano and
Hinze, 1994) and in deep keel of the western basin (e.g., Fig. 4; ), it seems possible that pre-1110 Ma volcanics may lie buried there.

**Early Stage** (1110-1106 Ma) – this stage is represented by reversed polarity lavas and intrusions of diverse compositions (ultramafic to felsic). All reversed volcanic sequences show similar chemostratigraphic sequences where early primitive basalts ($\text{mg#}>50$) give way to more diverse compositions that show evidence of crustal contamination ($\varepsilon_{\text{Nd}} < -2$, Th/Yb>1; Figs. 5, 6). Rhyolites with distinctly negative $\varepsilon_{\text{Nd}}$ values, thought to indicate crustal anatexis of Archean to Paleoproterozoic crust (Vervoort and Green, 1997; Vervoort et al., 2007), also begin to appear later in this early stage of volcanic activity. Nicholson et al. (1997) noted that geochemical characteristics of lower reversed sequences in western Lake Superior (NSVG, Powder Mill Group, and Osler Volcanic Group, Figs. 5, 6) can be reasonably correlated. However the basal western Lake Superior composition (Lower Siemens Creek) is not represented among the lower Mamainse Point units (MP1 and MP2, Fig. 5). Instead, the basal Mamainse Point basalts are geochemically similar to the Upper Siemens Creek in western Lake Superior.

**Hiatus Stage** (1105-1101 Ma) – this stage is characterized by a cessation of mafic magmatism and only intermittent felsic magmatism. An interesting aspect of the felsic magmatism during this stage is that it is best represented by the abundant occurrence of felsic clasts in the Copper Harbor Conglomerate in Upper Michigan (Fig. 5; Davis and Paces, 1990). Detrital zircons analyzed from a basal sandstone unit in the Copper Harbor Conglomerate yield ages ranging from 1106-1101 Ma (Davis and Paces, 1990). The paucity of significant felsic units in the underlying Portage Lake Volcanics suggests that these clasts (and zircons) were shed from rhyolitic composite volcanoes that were evidently eroded and not preserved in the volcanic rock record. Miller and Vervoort (1996) initially termed this the Latent Magmatic Stage so as to reflect their interpretation that this stage represents a period of magmatic underplating of the crust that is implied by geophysical models (e.g., Figs. 4 & 7). Hiatus stage is preferred because it is more descriptive and non-genetic.

**Main Stage** (1101-1094 Ma) – the bulk of preserved volcanic and intrusive rocks filling the MCR were emplaced during this stage, which occurred during a period of normal polarity. Although the magmatism involved a variety of magma compositions from primitive basalts to rhyolites as in the early stage magmatism, the mafic and minor intermediate compositions of the main stage show little evidence of crustal contamination ($\varepsilon_{\text{Nd}} = +2$ to -2; Th/Yb <1; Fig. 6). Nicholson et al. (1997) distinguished two basalt composition types within the PLV and normal polarity NSVG sequences based on mostly on TiO$_2$ abundance and $\text{mg#}$, with less evolved, low TiO$_2$ compositions being predominant. The uppermost parts of the NSVG and PLV sequences are commonly capped by primitive olivine tholeiitic basalts with very low incompatible element abundances. In the NSVG, this interval is represented by the Schroeder-Lutsen basalt sequence, which sits unconformably on the Upper Northeast (UNE) and Upper Southwest (USW) sequences. This composition also occurs in the upper part of the Mamainse Point section (MP7).

**Late Stage** (1094-1086 Ma) – this stage is characterized by intermittent and localized volcanic activity in a period otherwise dominated by deposition of immature detrital sediments. These eruptions are dominated by intermediate to felsic magmas. Although no upper crustal magmatism evidently occurred after 1086 Ma, migration of copper-bearing crustal fluids occurred along reversed faults as late as 1040 Ma (Bornhorst et al., 1988) and locally resulted in the deposition of native copper and silver within the upper reaches of the volcanic pile.
Figure 6. Magmatic evolution of the Midcontinent Rift interpreted from geochronology, lithostratigraphy (Fig. 5), and chemostratigraphy of volcanic sequences and intrusive rock suites (Fig. 3). Data includes that referenced in Figure 5. Attributes of the five magmatic stages are discussed in the text.

The significance of these magmatic stages in the context of the overall tectono-magmatic evolution of the MCR will be discussed in a later section (Fig. 8). A more complete description of evidence for the apparent hiatus in mafic magmatism is warranted here, however. Evidence for the Hiatus Stage is found among all exposed volcanic sequences in the western Lake Superior basin (Fig. 5). Age dating of
volcanic sequences straddling the major magnetic reversal shows a dramatic diminishment of eruption rates and a dominance of felsic volcanism. In the Wisconsin-Michigan border area, the major magnetic reversal occurs within the upper part of the 2- to 4-km-thick Kallander Creek Volcanics, which forms the upper formation of the Powder Mill Group (Fig. 3) and are dominated by intermediate to felsic flows (Nicholson et al., 1997). Two rhyolite flows which are stratigraphically separated by about 2 km and straddle the major magnetic reversal, yield ages of 1107.3±1.6 Ma (Davis and Green, 1997) and 1098.8±1.9 Ma (Zartman et al., 1997). In Minnesota, Davis and Green (1997) found a similar age difference (1107.6±2.5 - 1100.5±1.9 Ma) over a 350 m interval of mostly rhyolite and trachybasalt situated midway in the 6+ km-thick northeast limb of the North Shore Volcanic Group (Green, 1972). Thus, over half of the 13 million years of geologic time that is represented by the North Shore Volcanic Group is contained within less than 6% of its total stratigraphic thickness. Direct evidence for a similar diminution in mafic volcanic activity is not available from the Osler Group in Ontario (Fig. 3). However, a U-Pb age of 1105.3±2.1 Ma (Davis and Green, 1997) for a thick rhyolite flow that defines the upper part of the magnetically reversed section and separates two geochemically distinct basalt flow sequences, the upper and central suites (OGU and OGC in Fig. 5; Lightfoot et al., 1991), is consistent with such a possibility. Although no U-Pb ages of any type are found in the range of 1105-1102, Davis and Paces (1990) reported ages between 1106-1101 Ma for detrital zircons from a sandstone lense at the base of the Copper Harbor Conglomerate directly overlying the Portage Lake Volcanics on the Keweenaw Peninsula (Davis and Paces, 1990). This implies that any volcanoes that existed during the Hiatus Stage were exclusively felsic in the western part of the MCR. As described in more detail in the next section, U-Pb ages of intrusive rocks of the MCR indicate a similar hiatus in mafic magmatic activity between 1105 and 1101 Ma (Fig. 5).

Whereas the reduction in magmatic activity between 1107 and 1102 Ma appears to be real for the volcanic and intrusive suites in the western part of the MCR, it is not clear whether this reduction in mafic magma eruption is representative of the MCR as a whole. The recognition of two extra paleomagnetic reversals in the Mamainse Point Formation (Annells, 1973) may indicate more or less continuous eruption in the eastern basin, during the period between 1107 and 1100 Ma, while the western basin was in a relatively dormant stage. Previous attempts to correlate the Mamainse section with the western Lake Superior sequences interpreted the deposition of the polymict Great Conglomerate as likely correlative with the volcanic hiatus evident in the western sequences (e.g., Miller et al., 1995; Nicholson et al., 1997; Hollings et al., 2010). However the recent age of about 1100 Ma reported from just below the Great Conglomerate (Hysell-Swanson, pers. comm., 2012) indicates the unit was deposited at the onset of the main magmatic stage.

Integration of geochronologic and geophysical data has allowed for reasonable estimates of the rates of local volcanism and basin subsidence. Assuming the present volume of volcanics in the rift to be about 1.5 million km³ and an originally erupted volume of at least 2 million km³ (taking erosion into account), the average eruption rate for the MCR would have been about 0.15 km³/yr (Cannon, 1992). However, if an approximately 5 Ma hiatus in mafic volcanic activity is factored in, eruption rates during the early and main stages of volcanic activity were probably greater. For example, eruption rates of up to 0.2 km³/yr have been calculated for the thick Portage Lake Volcanics, assuming a total volume of about 500,000 km³ emplaced over a 2.2 m.y. period (Davis and Paces, 1990; Cannon, 1992). These rates are greater than modern ocean plume environments (Iceland 0.05 km³/yr; Hawaii 0.03-0.1 km³/yr), but are comparable to some continental flood basalt provinces (Columbia River 0.07-0.28 km³/yr; Parana, >0.24 km³/yr), and less than others (Deccan 0.4-1.0 km³/yr) (Swanson et al., 1975; Gallagher and Hawkesworth, 1994).
Based on similar data, Davis and Paces (1990) calculated a subsidence rate of 1.3 mm/yr for a 2850 m-thick interval of the Portage Lake Volcanics. Cannon (1992) calculated a similar value of 1.5 mm/yr for the average subsidence rate during all of main stage volcanism and estimated a range from 0.5 to 5 mm/yr. He estimated that subsidence after main stage volcanism slowed to an average rate of about 0.2 mm/yr. Eruption and subsidence rates during reversed polarity early stage volcanism was probably even greater. Although reversed volcanic sequences do not exceed 5 kilometers of exposed stratigraphic thickness (1.5 km - Mamainse Pt, Units 1-4, Annells, 1973; 2.4 km - Osler Gp, Lower and Central Suites, Lightfoot et al., 1991; 2.6 km - NSVG, lower NE sequence, Green, 2002; 4.8 km Powder Mill Group, Nicholson et al., 1997), U-Pb ages from reversed lava sequences tightly cluster in the range of 1109-1107Ma. If the 5 km-thick Powder Mill Group erupted within 2 million years, this would imply a subsidence rate of 2.5 mm/yr. Despite only 1.5 kilometers of the 5 km-thick Mamainse Point section being composed of reversed volcanics, modeling of magnetic, seismic and gravity data in the eastern lake basin (Mariano and Hinze, 1994a and b) indicates that reversed lavas thicken dramatically toward the axis of the rift basin where they comprise a thickness of up to 10 kilometers. If this thickness was erupted over the same 2 Ma timeframe as reversed lavas in the western part of the rift, it would imply a rate of lava accumulation of 5 mm/year. However, the recent discovery of reversed polarity intrusive rocks as old as 1117 Ma in the Lake Nipigon area (Heaman et al., 2007) hints that similar-aged volcanic rocks may lie at the base of reversed volcanic sequence in the eastern basin. Moreover, the discovery that the top of the uppermost reversed sequence at Mamainse Point has an age of about 1100 Ma (Hysell-Swanson, pers. comm., 2012) increases the upper age limit of reversed polarity lavas to well above 1106 Ma. Therefore, the inference of a 2 Ma eruption window for reversed polarity volcanism is unlikely.

**Intrusive Rocks of the Midcontinent Rift**

Intrusive igneous rocks associated with the development of the MCR are considered part of the Midcontinent Rift Intrusive Supersuite (Miller et al., 2002a,b). In his summary of MCR intrusions, Wieblen (1982) identified three general categories of intrusions that can be distinguished by volume, age range, emplacement history, geographic distribution, compositional range, and country rocks. These are 1) large subvolcanic intrusive complexes, 2) isolated alkalic and carbonatitic intrusions, 3) mafic dike and sills swarms. Since Wieblen’s compilation, a fourth type of intrusion has been identified as an important and distinctive class of intrusions - small ultramafic/mafic intrusions which commonly host Ni-Cu-PGE mineralization.

**Subvolcanic Intrusive Complexes**

The main subvolcanic intrusive complexes exposed in the Lake Superior basin are the Duluth Complex and Beaver Bay complexes emplaced into the North Shore Volcanic Group of northeastern Minnesota (Miller et al., 2002a,b) and the Mellen Complex emplaced into the Powder Mill Volcanic Group near the Michigan-Wisconsin border (Fitz, 2011; Fig. 3). All complexes were emplaced through multiple intrusive events of varied magma compositions into the lower to medial sections of MCR volcanic sequences. Although the difference in size between the Duluth and Mellen Complexes (Fig. 3) reflects, in part, the steeper rift-ward dip of the Mellen Complex, gravity data indicate that the Duluth Complex is significantly larger in volume. The Duluth Complex has a surface area of over 5,000 km², is situated over two of the largest Bouger gravity anomalies (>50 mgals) associated with the MCR, and is estimated to be rooted to a depth of as much as 13 kilometers (Allen et al., 1997). This implies a total volume between 35,000 and 40,000 km³. Multiple mafic to felsic intrusions emplaced higher in the NSVG volcanic
Edifice in northeastern Minnesota are distinguished from the deeper-seated Duluth Complex intrusions and are termed the Beaver Bay Complex and miscellaneous subvolcanic intrusions (Fig. 3).

The Mellen Complex of Wisconsin (Fig. 3) is a 1- to 5-kilometer thick, sheet-like complex composed of four main intrusions – the Potato River intrusion to the east, the Mellen granite in the center, Mineral Lake intrusion in the west, and the small Rearing Pond intrusion in the upper part of the Mineral Lake body. All were emplaced into the reversed polarity Powder Mill Group Volcanics during main stage (normal polarity) magmatism, though the 4.5-kilometer-thick Mineral Lake intrusion is floored by Paleoproterozoic and Archean rocks. Both the Mineral Lake and Potato River intrusions include lower olivine gabbroic cumulates, a thick midsection of gabbroic anorthosite cumulates, and a cap of granophyre. Granophyre from the Mineral Lake Intrusion yields a U-Pb age of 1102±2.8 Ma (Zartman et al., 1997). The Rearing Pond intrusion is a well differentiated layered mafic intrusion that grades from a lower dunite to an upper ferrogabbro (Olmsted, 1969). The Mellen granite is unlike any other felsic pluton intrusion in the MCR by virtue of its intergranular texture and preponderance of biotite; MCR granophyres typically display micrographic texture and contain prismatic ferropyroxene as the dominant mafic phase. The Mellen granite has a U-Pb age of 1100.9±1.4 Ma (Zartman et al., 1997) which, by the fact that it contains gabbro inclusions evidently derived from adjacent mafic intrusions, places an upper limit on the age of the Mellen Complex.

The Duluth Complex is composed of multiple mafic and felsic, sheet-like intrusions that were emplaced into the base of the NSVG volcanic edifice during the early and main magmatic stages of the MCR (Miller and Weiblen, 1990; Miller and Ripley, 1996; Miller and Severson, 2002b). Duluth Complex intrusions are routinely classified into four series based on their bulk composition, age, and internal structure – felsic, early gabbro, anorthositic, and layered (Fig. 7). The earliest intrusions include granophyric granite bodies of the felsic series, which are concentrated along the complex’s upper contact, and gabbroic to ferrodioritic mafic layered intrusions of the early gabbro series in the eastern arm of the complex. Both series display reversed polarity and yield U-Pb ages between 1109 and 1106 Ma (Paces and Miller, 1993; Vervoort et al., 2007). Where in contact, field relationships consistently imply that emplacement of granophyre preceded the gabbroic intrusions. The bulk of the exposed area of the Duluth Complex (>75%) was formed during the onset of the main stage of MCR magmatism with the formation of complex gabbroic to anorthositic cumulates of the anorthositic series and the emplacement of discrete, variably differentiated mafic layered intrusions of the layered series. Although field relationships consistently show that the anorthositic series was emplaced before the layered series, high precision U-Pb ages (errors < 0.5 Ma) of five layered series samples and four anorthositic series samples indicate that both series formed within a one million year period between 1099-1098 Ma (Paces and Miller, 1993; Davis and Green, 1997; Hoaglund, 2010). Hoaglund (2010) calculated the volume of layered series intrusions to conservatively be 15,000 km³ and the anorthositic series to be about 10,000 km³, which yields an average combined emplacement rate of about 0.025 km³/yr. Not knowing the amount of eroded material, this may rate may be considerably greater (double?).

The Beaver Bay Complex (BBC) is a hypabyssal, multiple-intrusive igneous complex exposed over a 600 km² area in northeastern Minnesota (Fig. 7; Miller and Chandler, 1997; Miller and Green, 2002a). The BBC and related hypabyssal intrusions were emplaced into the medial section of the North Shore Volcanic Group (USW and UNE sequences in Fig. 5). Thirteen intrusive units have been identified within the BBC, representing a minimum of six major intrusive events. With the exception of a body of granophyre, most intrusions were formed from gabbroic to dioritic parental magmas with successive intrusions generally involving less evolved compositions. U-Pb ages (Paces and Miller, 1993; Hoaglund, 2010) indicate that most BBC intrusions were emplaced at about 1096 Ma, about 3 million years after the
Duluth Complex (Fig. 5). However, the earliest intrusions of the BBC, as implied from field relations, have not yet been dated.

**Figure 7.** Geology of northeastern Minnesota showing the principal MCR-related intrusive and volcanic units. Also shown are the principal areas of Cu-Ni-PGE sulfide deposits.

**Alkaline and Carbonatitic Intrusions**

MCR-related alkaline and carbonatitic rocks occur in several intrusive complexes emplaced into Archean rocks north of Lake Superior (Fig. 3). The largest of these are the Coldwell and Killala Lake alkaline complexes and the Prairie Lake carbonatite, but also includes numerous small lamprophyric, carbonatitic and alkaline intrusions (Sage, 1991). As described below, alkalic and carbonatitic intrusive rocks related to the MCR host base, precious and rare metal occurrences (Smyk and Sage, 1995).

Most of these complexes are spatially localized and structurally controlled by the Trans-Superior Tectonic Zone (TSTZ, Fig. 3) and the Kapuskasing Structural Zone (Fig. 3). The Trans-Superior Tectonic Zone is a north-northeast-trending structure that extends for over 600 km and appears to link up with the Thiel Fault in Lake Superior (Klasner et al., 1982). Dickas and Mudrey (1997) interpret the Thiel-TSTZ structure to be a major accommodation zone in the segmentation of the MCR. The Kapuskasing Structural Zone varies from a broad zone of faulting at the east coast of Lake Superior to a
very narrow zone near Hudson Bay to the north. The zone contains west-dipping faults exposing an approximately 20 km thick section of Archean crust related to transpressive tectonics between 2.6 and 2.45 Ga (Percival and West, 1994). Sage and Watkinson (1995) suggested that these large-scale structures served to not only focus intrusion of alkalic and carbonatite magmas, but also were reactivated and played major roles in the structural development of the MCR.

Precise U-Pb ages for alkali and carbonatitic intrusions associated with the TSTZ range from 1150 to 1100 Ma (Smyk, 2010). The age dates plotted in Figure 5 are for the Coldwell Complex (1108 ± 1Ma, Heaman and Machado, 1993) and two carbonatite intrusions dated by Heaman et al. (2007) - Nemegosenda (1105.4 ± 2.6 Ma) and Lackner Lake (1100.6 ± 1.5 Ma.). Sage and Watkinson (1995) do not report precise ages for intrusions into the KSZ, but nevertheless interpret many of the small carbonatites, lamprophyres and alkaline intrusions to be related to the MCR.

The Coldwell Complex (Fig. 3) is the largest and most complex of the alkaline intrusions associated with the MCR. The sub-circular complex has a diameter of 25 km and covers an area of approximately 580 km² (Good et al., 2010). The complex is composed of three, superimposed ring complexes or magmatic centers that become progressively more alkalic (Mitchell and Platt, 1978).

Center 1: gabbro and iron-rich augite syenite
Center 2: alkalic biotite gabbro and nepheline syenite
Center 3: syenite and quartz syenite

Center 1 gabbroic rocks forming the eastern part of the complex contain Cu-Ni-PGE mineralization that is currently being evaluated for development (see Good, this volume). The superimposition of intrusive centres and a complex and protracted magmatic history have produced a myriad of hybrid rocks, igneous breccias and ambiguous cross-cutting relationships. Hornfels volcanic inclusions occur throughout the complex (Smyk, 2010), implying that the complex was likely emplaced beneath an edifice of MCR volcanics.

Mafic Dike and Sill Swarms

Mafic dikes, which likely served as feeders to flood basalts and subvolcanic intrusions, are found within and peripheral to the MCR in the Lake Superior basin (Fig. 3). In addition, thick mafic sills, subconformable sheets, and small intrusions are common in shallow-dipping Paleoproterozoic to Early Mesoproterozoic sedimentary sequences in the Lake Nipigon area, the MN-ON border area, and eastern Mesabi Range.

Green et al. (1987) compiled the lithologic, geochemical, structural and paleomagnetic attributes of mafic dike swarms associated with the MCR (Fig. 3). Whereas mafic dikes are locally well exposed, especially in Ontario, dike swarms that occur in pre-rift basement rocks are easily recognizable from high resolution aeromagnetic images where they stand out as positive or negative linear anomalies. Dikes also cut MCR volcanic and intrusive rocks, but are not as easily recognized on magnetic anomaly maps due to more subdued contrast with the country rock. Dike swarms generally strike parallel to the trend of the rift and span mafic compositional ranges typically found in the basaltic flows of the MCR. The width of most dikes ranges from 10 - 50 meters, but some can be as wide as 500 m. Although scant age dates have been obtained from the dike swarms, both normal and reversed polarity dikes are evident in most swarms. Typically, the orientations of each polarity type in a given swarm are only slightly different.

In the MN-ON border area, Hollings et al. (2010, 2012) recently delineated several dike swarms with distinct orientations, magnetic polarities, and compositional attributes. The dominant swarm is the Pigeon River dike swarm, which trends east-northeast to northeast (rift parallel) and dips steeply to the southeast. Although dike compositions range in mg#, Hollings et al. (2010) distinguished two...
compositional types, a low TiO$_2$-Gd/Yb group and, a less common, high TiO$_2$-Gd/Yb group, which are similar to the compositional differences between nearby Logan and Nipigon Sills (see below). The Pigeon River dikes have not been dated radiometrically; however, they show normal magnetic polarity and thus are thought to have been emplaced during main stage magmatism. The northwest-trending Cloud River dike swarm is compositionally similar to the low TiO$_2$-Gd/Yb Pigeon River dikes, but appears to be older as this swarm is reversely polarized and yields an U-Pb age of 1109.2±4.2 Ma. The strike orientation of the large Pine River-Mt. Mollie composite dike curves from NE (where it is subparallel to the Pigeon River dikes) to E-W (where it appears to merge with the 1099.6±1.2 Ma Crystal Lake gabbro). It has reversed polarity and yields an age of 1109.3±6.3 Ma, similar to the Cloud River dikes.

Mafic sills are also common in the MN-ON border area and around Lake Nipigon where they produce a dramatic mesa-like topography. Although all MCR-related sills in this region were originally called Logan Sills (Sutcliffe, 1987; Smith and Sutcliffe, 1989), Hollings et al. (2007b, 2010) have shown that the sills in the Lake Nipigon area have more diverse compositions and are characterized by low TiO$_2$ and Gd/Yb, whereas sills south of Thunder Bay are more consistently evolved (mg#$<40$) and have elevated TiO$_2$ and Gd/Yb. They recommend distinguishing Nipigon Sills as those occurring north of Thunder Bay from the Logan sills to the south. Hart and MacDonald (2007) report four main Nipigon sills, ranging from <5 m to >180 m in thickness, occur as sub-conformable bodies intruded into the 13 Geon Sibley Group sedimentary rocks. Weiblen et al. (1972) and Smith and Sutcliffe (1989) report six major Logan Sills in the international border area where they occur as semi-conformable sheets within the sub-horizontal Paleoproterozoic (1.84-1.78 Ga) Rove Formation (Hollings et al., 2010). They typically range in thickness between 3 m and 20 m, with a maximum of 50 m.

Ultramafic-Mafic Intrusions

An increasing number of small ultramafic to mafic intrusions related to the MCR have been discovered over the past decade due to expanded exploration for Ni-Cu-PGE deposits commonly associated with such intrusions. The currently identified intrusions (Fig. 3) typically occur in Paleoproterozoic metasedimentary rocks in Minnesota (Tamarack - Goldner, 2011) and Upper Michigan (Eagle - Ding et al., 2011; BIC - Rossell, 2008; Foley, 2011; Roland Lake – Schulz and Nicholson, 2009) or in Archean to middle Mesoproterozoic rocks in the Thunder Bay – Lake Nipigon areas of Ontario (Current Lake, Seagull, Disreali, Hele, Kitto, Shillabeer, Jackfish Island, and Riverdale - Hart and MacDonald, 2007; Goodgame et al., 2010; Hollings et al., 2007b, 2007c, 2010, 2012). Those that have been dated radiometrically consistently show these intrusions to be correlative with the initiation and early stage of MCR magmatism (1115 – 1105 Ma, Fig. 3).

The size and shapes of the MCR ultramafic-mafic intrusions are quite variable. All intrusions are less than one kilometer thick and cover a limited area between 84 km$^2$ (Seagull - Hollings et al., 2007) and 0.1 km$^2$ (Eagle - Ding et al., 2010). Intrusion shapes include sheet-like (Shillabeer, Jackfish, Disreali, Hele, and Kitto), lopolithic (Seagull), bowl-shaped (BIC), elliptical cone-shaped (Eagle), and chonolithic (Current Lake, Tamarack). Although the unexposed, tube-like Current Lake intrusion north of Thunder Bay is known to be 50 m to 600 m wide and 6 km long, a network of linear aeromagnetic anomalies related to it covers a 12 km by 6 km area that continues to be explored (Goodgame et al., 2010).

All intrusions contain a lower ultramafic section composed olivine and pyroxene cumulates that, in most cases, is overlain by mafic cumulates composed of plagioclase, pyroxene and commonly Fe-Ti oxide. The exceptions to this are the Eagle and Current Lake intrusions, which are entirely composed of
lherzolitic (Ol+Opx+Cpx) cumulates with 15-40% intercumulus plagioclase (Ding et al., 2010; Goodgame et al., 2010). Where a mafic cap in the upper portion of these intrusions is missing, as at the Eagle intrusion, erosion of the upper part of intrusion may be the cause. The lack of a mafic component to the Current Lake intrusion may be related to its narrow tube-like shape, although, as found at Tamarack (Goldner, 2010), a more complete differentiated sequence may be found where the intrusion widens out (e.g., Southeast Anomaly zone (MacTavish and Smyk, 2010)). The specific cumulate paragenesis is not similar in all intrusions. For example, the Tamarack intrusion of Minnesota displays a cumulate paragenetic sequence of Ol → Ol+Opx+Cpx → Pl+Cpx+Opx → Pl+Cpx+Opx+FeOx+Ol (Goldner, 2011). In contrast, the BIC intrusion of Upper Michigan shows a paragenetic sequence of Ol → Cpx+Ol → Cpx+FeOx+Ol → Pl+Cpx+FeOx (Foley, 2011).

Because the ultramafic-mafic intrusions were emplaced into pre-MCR rocks, most intrusions develop marginal chill zones that, when corrected for accumulated olivine, can be used to estimate parent magma compositions (Goldner, 2011; Foley, 2011, Miller et al., 2011). These estimates indicate similarities in major and trace elements to picritic lavas commonly found in early reversed MCR lava sequences (Hollings et al., 2007b; Ding, 2010; Goldner, 2011; Foley, 2011). The volatile-rich compositions of these parent magmas are indicated by the abundance of primary amphibole, biotite, carbonate, and sulfide (Goldner, 2011; Foley, 2011; Heggie, 2005). Incompatible trace elements show a pronounced enrichment trend similar to OIB compositions, though moderately to slightly negative Nb-Ta anomalies are common (Hollings et al., 2007b; Goldner, 2011; Foley, 2011). Negative Nb-Ta anomalies are not uncommon to continental flood basalts in general (Campbell, 2001) and are common attributes of MCR volcanics (Nicholson et al., 1997). Such anomalies may indicate contamination of OIB-type (plume-generated) magmas with continental crust or by subcontinental lithospheric mantle possibly containing recycled crust from Archean subduction (Shirey, 1997; Hollings et al., 2007b, 2010, 2012).

**Sedimentary Rocks of the Midcontinent Rift**

The largely fluvial redbed sedimentary rocks that fill the rift include four lithostratigraphic groups: 1) thin pre-volcanic, quartzose fluvial and lacustrine deposits; 2) syn-volcanic, interfloow volcano-clastic sedimentary rocks; 3) post-volcanic, immature sedimentary rocks of the Oronto Group and equivalents; and 4) quartzose sandstone of the Bayfield Group and Jacobsville Sandstone (Ojakangas and Morey, 1982). The flat-lying Sibley Group sedimentary rocks exposed in the Lake Nipigon area and intruded by early MCR intrusions (Fig 3) are distinctly older than the MCR at 1350-1300 Ma (Franklin et al., 1980) and are unconformably overlain by pre-volcanic MCR sedimentary rocks (Hollings et al., 2007b). Although Franklin et al. (1980) speculated that the Nipigon Embayment represents a failed third arm aulocogen of the MCR, others (Fralick and Kissin, 1995; Hollings et al., 2004; Rogala et al., 2007) have suggested that the Sibley Group was deposited in a half-graben related to a 1350 Ma anorogenic thermal event, some 200Ma before the MCR.

Quartzose sandstone, siltstone, and minor quartz pebble conglomerate underlie early MCR volcanics in four different areas in the Lake Superior region (Fig. 5). These pre-volcanic units include: 1) the Bessemer Quartzite in the Wisconsin-Michigan border area occurring beneath the Powder Mill Volcanic Group, 2) the Nopeming Sandstone near Duluth, Minnesota occurring beneath the lower southwestern sequence of the North Shore Volcanic Group; 3) the Puckwunge Sandstone in near Grand Portage,
Minnesota beneath the lower northeastern sequence of the North Shore Volcanic Group; and 4) the Simpson Island Formation forming the base of the Osler Volcanic Group northeast of Thunder Bay, Ontario. Bedding features of the Nopeming, Puckwunge, and Simpson Island units imply fluvial deposition in a braided stream environment, whereas bipolar paleocurrent indicators in the Bessemer Quartzite imply tidal or longshore influences (Ojakangas and Morey, 1982, Hollings et al., 2007b).

Coarse, immature, polymict sandstones and conglomerates (lithic arkose to feldspathic lithic arenite) occur as interflow sedimentary units throughout all volcanic sequences. Sources of detritus include felsic and mafic volcanic rocks, mafic intrusive rocks and non-MCR rocks outside the rift basin (Green, 2002). All paleocurrent indicators show generally basinward vectors (Merk and Jirsa, 1982). In the Mamainse Point Volcanic Group, interflow conglomerates and minor sandstones comprise almost one quarter of the volcanic-sedimentary sequence, with the Great Conglomerate unit itself being over 500m thick (Annels, 1973). Interflow sedimentary units in the Portage Lake Volcanic Group are well known because they host many of the principal native copper deposits on the Keweenaw Peninsula of Michigan. A total of 22 interflow units vary in thickness from tens of centimeters to as much a 120 meters and are dominated by conglomerates. These interflow units comprise about 3 percent of the total thickness of the Portage Lake Volcanics (Merk and Jirsa, 1982). On Isle Royale, interflow sedimentary units make up 10 to 15 percent of the Portage Lake sequence. Interflow sedimentary units in the North Shore Volcanic Group comprise about 4 percent of the sequence and tend to be dominated by sandstone (Jirsa, 1978; Green, 2002). The thickest unit is the 100m-thick Cut Face Creek sandstone that forms the base of the uppermost Schroeder-Lutsen Sequence and rests unconformably on older volcanics (Fig. 5).

During the waning of volcanic activity during the Late Magmatic Stage, continued subsidence of the rift grabens resulted in accumulations of up to 8 kilometers of conglomerate, sandstone and siltstone intercalated with localized volcanic eruptions (Cannon, 1992). These generally immature sedimentary rocks are collectively termed the Oronto Group. Where it is exposed in Michigan, Wisconsin and Isle Royale, the Oronto Group is subdivided into three formational units: the Copper Harbor Conglomerate, the Nonesuch Shale, and the Freda Sandstone. The Copper Harbor Conglomerate is a lens-shaped red bed unit with a maximum thickness of 1830 meters that fines upward and basinward from a volcanic clast-dominated conglomerate to lithic subarkose sandstone (Daniels, 1982). The unit is interpreted as a prograding alluvial fan complex developed basinward of graben-bounding faults (Keweenaw Fault and Isle Royale Fault in Fig. 3). The Nonesuch Shale, which interfingers with the upper Copper Harbor Conglomerate, is an oxidized sequence of siltstone, shale, and sandstone with a high hydrocarbon and sulfur content (Daniels, 1982). The Nonesuch, which is up to 215 meters thick, is interpreted to have formed in a closed lacustrine basin. Its carbon- and sulfur-rich composition appears to have been key to the formation of stratiform Cu-sulfide deposits (Swenson et al., 2004), as will be discussed later. The Freda Sandstone is a red-bed sequence of arkosic to quartzose sandstone and shale up to 3660 meters thick (Daniels, 1982). It is interpreted to be fluvial in origin.

The final phase of sedimentation occurred when the extensional tectonics of rifting was replaced by compressional stresses generated during Grenville orogenesis between 1080-1040 Ma (Cannon, 1994). This northwest-directed compression caused graben-bounding normal faults to be transformed into reverse-thrust faults and resulted in an inversion of the rift with the creation of a central horst bounded by flanking basins. With the formation of a central horst in some segments of the rift basin, the Oronto Group sediments were locally reworked and deposited into the marginal basins along with sediments derived from outside the MCR basin. Geophysical models infer that sedimentary thicknesses in the marginal basins of as much as 3 kilometers (Hinze et al., 1982; Chandler et al., 1989; Allen et al., 1997). These feldspathic to quartzose red-bed sandstones are called the Bayfield Group in Minnesota and
Wisconsin (Morey and Ojakangas, 1982) and the Jacobsville Sandstone in eastern Lake Superior (Kalliokoski, 1982). In northwestern Wisconsin, the Bayfield Group is subdivided into the feldspathic Orienta Sandstone, the quartzose Devils Island Sandstone, and the feldspathic Chequamegon Sandstone. In eastern Minnesota, the principal formational units are the feldspathic Fond du Lac Formation, and the more quartzose Hinkley Sandstone. All Bayfield Group/Jacobsville units are interpreted to have formed in fluvial to lacustrine sedimentary environments.

Tectono-magmatic Evolution of the Midcontinent Rift

Although considerable debate has arisen over the past decade regarding the role, extent, and even the existence of mantle plumes (Buchan and Ernst, 2001; Foulger et al., 2005; Foulger and Jurdy, 2007), most workers on the Midcontinent Rift attribute its tectonic and magmatic evolution to the influence of a starting mantle plume (Hutchinson et al., 1990; Nicholson and Shirey, 1990; Cannon and Hinze, 1992; Shirey et al., 1994; Miller et al., 1995; Miller and Vervoort, 1996; White, 1997; Hinze et al., 1997; Davis and Green, 1997; Shirey, 1997; Nicholson et al., 1997; Wirth et al., 1997; Vervoort and Green, 1997; Hollings et al., 2007b; Heaman et al., 2007; Vervoort et al., 2007; Hollings et al., 2010; Hollings et al., 2012).

Most of these studies argue that the geologic, geochemical, geophysical and geochronologic attributes of Midcontinent Rift in the Lake Superior area are best explained by chemical and physical processes attending the arrival of an anomalously hot starting mantle plume at the base of the lithosphere at about 1115 Ma. Evidence in support of a plume model includes the estimated volume of more than 2 million km$^3$ of erupted material (Cannon, 1992), based on seismic reflection data, and a nearly equivalent amount of magma underplated and intruded into the crust as suggested by gravity data (Behrendt et al., 1990, Trehu et al., 1991; Hinze et al., 1992; Mariano and Hinze, 1994b; Thomas and Teskey, 1994). This volume of magma requires an anomalously hot mantle source such as would be expected from a mantle plume (Hutchinson et al., 1990). Cannon and Hinze (1992) argued that if the Nipigon Embayment is taken to represent the failed third arm of the MCR, as suggested by some (Franklin et al., 1980; Sutcliffe, 1987; Lightfoot et al., 1991), but questioned by others (Fralick and Kissin, 1995; Hollings et al., 2004; Rogala et al., 2007; Hart and MacDonald, 2007), a radial pattern of dike swarms that is centered near Thunder Bay would be consistent with a triple junction generated by the impact of a mantle plume. Radiogenic isotope and trace elements of most mafic rocks of the MCR are also consistent with their derivation from an undepleted mantle plume (Nicholson and Shirey, 1990; Shirey et al., 1994; Nicholson et al., 1997; Shirey, 1997; Hollings et al., 2007c; Hollings et al., 2010; Hollings et al., 2011). Indeed, the fact that the earliest volcanic products show undepleted mantle isotopic signatures at a time of minimal lithospheric extension demonstrates that a rising plume was involved in the rifting process from the onset and was probably an integral force that drove extension and thinning of the lithosphere (Cannon and Hinze, 1992; Nicholson et al., 1997).

The 30 Ma duration of MCR magmatism is perhaps its most difficult characteristic to rectify with a mantle plume model (Hill, 1991; Campbell, 2001; Ernst et al., 2005). The duration of plume-related magmatism associated with most Mesozoic to Tertiary LIPs is only a few million years (Coffin and Edholm, 1994; Ernst and Buchan, 2001b). This becomes an even greater problem if MCR magmatism is extended back to 1150 Ma as suggested by Heaman et al. (2007). Hollings et al. (2011) has suggested that this prolonged magmatism may indicate the MCR was affected by a mantle plume cluster as proposed by Ernst and Buchan (2002) to explain the 2.4 Ga long-lived Matachewan and Mistassini event. Another explanation for prolonged multimodal magmatism is that proposed by Bercovici and Mahoney (1994), whereby a starting plume head stalls at the 670 km discontinuity and creates a double-headed
plume that subsequently results in two main phases of magmatism separated by tens of millions of years. The problem with any multi-plume model for the MCR is that paleomagnetic data imply that Laurentia was drifting at a rate of 20-40 cm/yr (Swanson-Hysell et al., 2009; this volume) making it unlikely in the case of a double-headed plume, and fortuitous in the case of plume cluster, that plume heads would impact the same spot on the lithosphere.

As pointed out by Campbell (2001), “the time difference between the onset of volcanism and the start of runaway extension is dependent on the strength of the lithosphere prior to the arrival of the plume and on the magnitude of the subduction-related forces acting on the plate. The observed difference can range from 1 to 20 m.y. (Hill, 1991)”. By the end of main stage magmatism (1094 Ma), the plume component (e.g., basalts with $\varepsilon_{Nd} \approx 0$) appears to be waning and thus the period of “plume” magmatism may be closer to 20 Ma, a less problematic duration. A six-stage tectono-magmatic model is proposed here (Fig. 8) that attempts to account for the various geochemical, geochronologic, and structural attributes of the MCR by a single starting mantle plume impacting and embedding its plume head into the base of the Laurentian lithosphere at around 1115 Ma.

Stage I (1115-1110 Ma) – Plume Impact and Crustal Doming - The recent discovery of a mix of mafic to ultramafic intrusions in the Nipigon Embayment area with emplacement ages between 1115 and 1110 Ma (Heaman et al., 2007) and an apparent lack of volcanic rocks of this age has compelled a rethinking about the timing and the tectonic effects of mantle plume impact with the base of the lithosphere. The lack of volcanic ages older than 1109 Ma (Fig. 5) may simply reflect the inability to find dateable material in the lowermost flows, especially the more primitive picritic compositions. However, given that these lower volcanic sequences do not exceed 1.5 kilometers in thickness and generally lack weathered flow tops or significant intervals of interflow sediments (Green, 1982; Nicholson et al., 1997) implies that they were likely erupted over a relatively short time period (<1-2 Ma?). However, this may hold true only for the exposed volcanics, which occur on the flanks of the MCR basin. The increased thickness of reversed polarity volcanics geophysically modeled in the axis of the MCR (up to 10km in the eastern basin, Mariano and Hinze, 1994a), leaves open the possibility that 1115-1110 Ma-aged volcanics may be preserved in the keel of the rift basin.

Tectonomagmatic models developed before the discovery of intrusive ages older than 1110 Ma (e.g., Cannon, 1992; Miller and Vervoort, 1996; Nicholson et al., 1997; Vervoort et al., 2007) reasoned that plume impact occurred around 1110-1109 Ma, the earliest age of most reversed polarity volcanics and many intrusions (Fig. 5), and immediately produced broad rapid volcanism. The older age dates for Nipigon Embayment intrusions (Heaman et al., 2007), which have undepleted mantle signatures indicative of deep (garnet-bearing) sources (Hollings et al., 2007a and 2007c), imply that plume impact may have occurred closer to 1115 Ma. The apparent lack of similar-aged volcanics, which would be expected to have been fed from these hypabyssal intrusions, may indicate that the flows were being eroded during a period of crustal doming. Campbell (2001) argues that the broad (1000-2000 km diameter) thermal anomaly introduced by the arrival of a starting plume head beneath continental lithosphere should lead to widespread uplift prior to the onset of rapid volcanism.

Stage II (1110-1105 Ma) Rapid Plateau Volcanism and Onset of Crustal Underplating - The onset of volcanism and associated intrusions into the MCR represented by the Early Magmatic Stage was characterized by the rapid eruption of initially primitive magmas that gave way to evolved and contaminated compositions. Seismic models imply that volcanic accumulations during this period occurred over a broad area and were not confined to a narrow graben (Cannon, 1992). The compositional
and chronologic correlations of early volcanic sequences underlain by fluvial to lacustrine sediments in the western part of the MCR suggest that a broad depression had begun to form within the broader crustal uplift. Given the greater thickness of reversed polarity volcanics in the eastern Lake Superior basin, it seems likely that subsidence was initiated earlier or occurred more rapidly than in the west.

This stage likely represents the progressive imbedding of the mantle plume head into the subcontinental lithospheric mantle (SCLM). Magmas generated from the plume initially rose quickly through the cool and brittle lithosphere generating the lower primitive volcanics observed at the bases of most volcanic sequences (Fig. 5; Siemens Creek, Lower Osler, Grand Portage lavas of the lower NE sequence of the NSVG; Units 1 and 2 of the Maimanse Volcanics) and early mafic intrusions (e.g., Disraeli, Kitto diabase, Heaman et al., 2007). The rapid heating of the crust by early mantle-derived melts and the onset of their staging in the lower crust likely led to variably evolved mafic magmas with crustal contamination signatures, the onset of felsic magmatism by crustal anatexis, and the occurrence of plagioclase porphyritic magmas. This produced the compositionally variable and contaminated Hovland lavas of the lower NE sequence of the NSVG, the Central Suite of the Osler, the Lower Kallander Creek lavas of the Powder Mill Group, and Groups 3-5 of the Maimainse Point Formation (Fig. 5). In the intrusive rocks, the latter part of this early stage is represented by the ferrogabbroic Logan sills, the Nipigon sills, the Early Gabbroic Series and Felsic Series of the Duluth Complex, and the alkaline rocks of the Coldwell Complex. At the waning of the early magmatic stages, mafic magmas show the greatest signs of crustal contamination - negative \( \varepsilon_{Nd} \) values and elevated Th/Yb ratios (Fig. 6). This is taken as evidence of the onset of extensive magma underplating of the crust resulting in crustal assimilation and anatectic melting to produce felsic magmas. The appearance of plagioclase phenocryst-rich volcanics in the upper parts of the reversed polarity lava sequences and diabase sills (Logan and Nipigon) and dikes is also consistent with deep crustal staging, where high pressures will promote plagioclase flotation (Kushiro, 1980).

**Stage III (1105-1101 Ma) Volcanic Hiatus and Extensive Crustal Underplating** - During this stage, magmatic activity within the rift was largely dormant, except for periodic rhyolitic volcanism. Deposition of high energy sediments indicates that some degree of vertical subsidence was occurring and that graben bounding faults were beginning to develop. Miller and Vervoort (1996) called this the latent magmatic stage of the MCR because they interpreted it to represent a period of continued mantle plume melting and storage of those melts almost exclusively in the lower crust by extensive crustal underplating. Gravity models over Lake Superior (e.g., Fig. 4, Behrendt et al., 1990, Trehu et al., 1991; Hinze et al,
Figure 8. Six-stage tectono-magmatic model for evolution of the Midcontinent Rift, interpreted from data presented in Figs. 5 & 6 and discussed in text.
1992 & 1997; Mariano and Hinze, 1994b; Thomas and Teskey, 1994) indicate that a mafic lens up to 15 kilometers thick occurs at the base of the crust beneath the axis of the MCR. Magmatic underplating, which likely started during the later part of the early magmatic stage, was probably instigated by the heating and anatexis of the lower crust caused by the passage of the earliest mantle-derived magmas coupled with heating from the rising plume. The creation of felsic melts and an increasingly ductile lower crust would have created density and rheologic barriers to impede the passage of mafic melts and promote their ponding at the Moho. Once initiated, mafic magma chambers would have continued to expand as additional rising mantle melts became trapped and triggered more widespread melting of the lower crust. At the peak of the latent/hiatus stage, the lower crust may have been largely impermeable to mafic magmas. Such a process of magma underplating of the lower crust bringing about a volcanic hiatus is envisioned to be a common phenomenon in the evolution of continental flood basalt provinces (Huppert and Sparks, 1988; Cox, 1993; Campbell, 2001).

To the extent that lithospheric thinning and extension was driven by the bouyancy and thermal energy of the starting mantle plume (e.g., Campbell and Griffiths, 1990), perhaps magma underplating actually caused diminished extension of the upper crust by delaminating and structurally decoupling it from the lower crust and lithospheric mantle. Although the resumption of volcanic activity at about 1102-1100 Ma (earlier near the axis of the rift) may have been externally triggered by increased extension of the crust, it seems also possible that “density cleansing of the lower crust” (Huppert and Sparks, 1988) caused by the migration of low density anatectic melts and perhaps thinning and shouldering aside of the ductile lower crust concomitant with magma underplating may have played important roles in allowing basaltic magmas to ultimately emerge from deep crustal magma chambers and bringing on the main magmatic stage.

Stage IV (1101-1094 Ma) Graben-bounded Volcanism and Evacuation of Lower Crustal Magma Chambers -The renewal of volcanic and intrusive activity during the main magmatic stage was characterized by rapid to moderate rates of eruption of uncontaminated (save rhyolite), but diverse magma compositions (Fig. 6). This stage is thought to represent the onset of upper crustal separation, the evacuation of evolved lower crustal magma chambers, and continued, but waning mantle plume melting. The main stage is represented by the nearly 10 km thickness of normally polarized North Shore Volcanic Group lavas in Minnesota and at least 5 km of Portage Lake Volcanics in Michigan, as well as major parts of the Duluth, Beaver Bay and Mellen intrusive complexes. Seismic reflection data clearly show that main stage volcanism was largely confined to rapidly subsiding asymmetric grabens bounded by listric normal faults and transected by accommodation zones (Cannon, 1992; Dickas and Mudrey, 1997).

The first few million years of main stage magmatism involved a differentiated range of tholeiitic basalt and minor felsic compositions (Fig. 6). Many of the earliest magmas were plagioclase-phyric magmas that created the extensive anorthositic series of the Duluth Complex (Fig. 7). Miller and Weiblen (1990) interpreted these plagioclase crystal mushes as derived from lower crustal magma chambers in which plagioclase was bouyant. They further speculated that the nearly pure anorthosite inclusions found in the Beaver Bay Complex are xenoliths derived from the roof zones of these deep chambers.

Although the main stage magmas were initially variably differentiated, they showed little in the way of the crustal contamination that characterized the end of the early magmatic stage (Fig. 6). This probably resulted from the development of thick marginal zones around long-lived lower crustal magma chambers, which effectively insulated the fractionally crystallizing magmas from interacting with the crust. As main stage magmatism progressed, however, magma compositions came to be dominated by primitive to mildly evolved, high-Al olivine tholeiitic basalts, as characterized by the Portage Lake
Volcanics (Paces and Bell, 1989) and the Schroeder-Lutsen basalts which lie atop the North Shore Volcanic Group (Green, 1972). This suggests that the residence time of mantle derived magmas decreased as the plumbing system of the upper crust became better developed.

Felsic magmas continued to be generated by crustal melting during main stage magmatism. However, in Minnesota, Vervoort and Green (1997) note that the $\varepsilon_{Nd}$ values of rhyolites are progressively more negative up section (Fig. 6). Vervoort et al. (2007) speculate that the source of felsic magmas migrated to shallower crustal levels over time with early melts derived from Paleoproterozoic-aged lower crust and younger melts generated from Archean crustal rocks. In the interior of the deepening grabens, small-volume rhyolites on Keweenaw Peninsula and Michipicoten Island were derived from remelting of early MCR basalts and do not show interaction with older basement crust (Nicholson and Shirey, 1990).

Stage V (1094-1080 Ma) – Thermal Collapse and Sedimentation - As volcanism waned due to the thermal decline of the mantle plume head and the likely detachment of the plume tail due to plate motion, the subsidence of central grabens continued (Fig. 7D). The central axis of the rift grabens became filled with a thick accumulation of alluvial fan, fluvial and some lacustrine sediments to form the Oronto Group. Intermittent volcanism became more localized and more differentiated with the last recorded activity occurring around 1086 Ma. The final melts generated in the Lake Superior region appear to be mixtures of plume and depleted asthenospheric mantle based on the occurrence of N-MORB-like compositions with slightly positive $\varepsilon_{Nd}$ values (Fig. 6). Nicholson et al. (1997) interpreted these magmas as indicating the displacement of the lithospheric mantle and its replacement by vestiges of the plume head and shallow asthenospheric mantle that infilled behind the dissipated head of the plume. Given paleomagnetic data that indicate rapid drift of the Laurentian plate (Swanson-Hysell et al., this volume), it is likely that the plume tail became detached from the plume head soon after the head became imbedded into the SCLM (i.e., during Stage II). Approximately 1.1 Ga mafic dikes are well known in the southwest US (Donadini et al., 2011) which is consistent with paleomagnetic data indicating a general drift of the plate to the northeast relative to a fixed plume. With the thermal decline of the mantle plume head, the rift experienced thermal collapse and sediment loading and the graben became filled with as much as 8 kilometers of sediments.

Stage VI (1080-1040) – Compression and Tectonic Inversion - Cannon (1994) has hypothesized that the tectonic inversion of the rift by reverse faulting on originally normal graben-bounding faults (Fig. 3) probably began around the time of the last volcanic eruptions at about 1086 Ma and may have continued until 1040 Ma. Bornhorst et al. (1988) report Rb-Sr isochron ages between 1060 and 1045 Ma for late-stage mineralization occurring along the Keweenaw Fault (Bornhorst et al., 1988). Cannon (1994) further reasoned that the compression may have been due to rejuvenation of compression within the Grenville Orogen with onset of the Ottowan phase at about 1090 Ma (McEachern and van Breemen, 1993). The northeast-directed regional compression resulted in about 30 kilometers of shortening and the creation of a central horst along most of the southwest arm of the MCR. Modeling of seismic data from the eastern Lake Superior basin and bedrock exposures along the northeast shore indicate that the effects of this compression on the southeast arm of the MCR evidently produced strike-slip motion along the graben-bounding faults, roll-over structures, northeast-trending folds and northwest-directed thrust faults (Mason and Halls, 1994; Samson and West, 1994; Mariano and Hinze, 1994a & b).

Despite the antiquity of the MCR compared to other large igneous provinces, it appears that the mantle plume dynamics and compositions that influenced Mesozoic to Tertiary continental rifting and flood basalt volcanism were fundamentally the same as those that affected the Midcontinent Rift. One
notable difference between the MCR and more recent plume-influenced LIPs is the prolonged period of magmatism. Shirey et al. (1994) pointed out that the magmatic progression seen in the MCR is similar in many ways to other continental flood basalt provinces. Because the MCR presents one of the most completely exposed sections of flood basalts, by virtue of its incomplete rifting and later tectonic inversion, its tectono-magmatic evolution may provide a test and constraints of general models of plume-generated continental rifting and large igneous province magmatism.

Mineral Deposits Related to the Midcontinent Rift

The MCR hosts two major classes of mineral deposits, hydrothermal and magmatic (Nicholson et al., 1992). All important mineral production in this region to date has come from the world-class hydrothermal deposits, whereas mineral deposits related to intrusive igneous rocks have provided only a small fraction of the total mineral production from the rift. That picture is about to change dramatically. At the time of this writing, over a dozen magmatic sulfide deposits are in the advanced exploration, environmental and mine permitting, or mine development stage of activity. The following summary of rift-related mineralization is drawn in large part from Nicholson et al. (1992) and Miller et al. (1995), Smyk and Franklin (2007), and the references therein.

Hydrothermal Deposits

MCR-related hydrothermal deposits include four main types: 1) native copper and silver deposits in basalts and interflow sediments; 2) stratabound copper sulfide and native copper; 3) copper sulfide veins and lodes hosted by rift-related volcanic rocks; and 4) polymetallic veins in the surrounding Archean and Paleoproterozoic country rocks (Fig. 9; Nicholson et al., 1992). The scarcity of sulfur within the rift rocks resulted in the formation of very large deposits of native metals. Where hydrothermal sulfides occur (i.e., shale-hosted copper sulfides), the source of sulfur was evidently local sedimentary rocks.

Native Copper and Silver Deposits- The native copper (and minor silver) deposits of the Keweenaw Peninsula have a long history of prehistoric mining and modern production that began in the 1840s. These deposits were the principal source of copper for the United States for many years, yielding more than 5 million metric tons of refined Cu from 1845 until the 1960's when the last mines closed. In addition to the Keweenaw Peninsula deposits, native copper and silver is found in virtually all exposed mafic volcanic sequences associated with the MCR, as well as in Oronto Group and Sibley Group sedimentary rocks (Nicholson et al., 1992; Smyk and Franklin, 2007). Native copper, locally accompanied by small amounts of native silver, occurs in the brecciated and vesicular tops of basalt flows (amygdular lodes), in interflow sedimentary rocks (conglomerate lodes), and in cross-cutting veins (fissures) (White, 1968). The copper typically fills open-spaces or replaces basalt. The major native copper deposits occur in zones where prehnite and pumpellyite are the major alteration minerals and epidote is absent or scarce (see Stoiber and Davidson, 1959; Jolly, 1974; and Livnat, 1983, for discussions of alteration patterns).
**Figure 9.** Occurrence of hydrothermal ore deposits associated with the Midcontinent Rift in the Lake Superior region (modified from Nicholson et al., 1992).

**Stratabound Copper Sulfide Deposits** - At the White Pine mine in Michigan, which was in production from 1953 to 1996, sedimentary copper sulfide and native copper deposits in the lowermost part of the Nonesuch Formation comprise one of the world's largest shale-hosted copper deposits (Ensign and others, 1968; Brown, 1971; Kelly and Nishioka, 1985; Mauk and others, 1989a, 1989b; Seasor and Brown, 1989; Swenson et al., 2004). In the area of active mining, the ore body is estimated to contain about 200 million tons (181 million mt) of ore with an average grade of 1.1% Cu and 0.25 oz (9 g) Ag/ton (Mauk and others, 1989a). A total of 4.5 billion lbs Cu and 50 million oz of Ag were produced over the life of the mine. At White Pine, the copper is mostly stratabound within the most organic-rich beds of the Nonesuch Formation. Two stages of mineralization are recognized (Mauk and others, 1989a, 1989b): 1) chalcocite layers formed during the main stage of mineralization, probably as a result of late diagenesis, accounting for 80-90% of the contained copper; and 2) during the second stage, native copper was deposited largely in structurally disturbed zones, mostly the result of (post-rift) thrust faulting.

The recently discovered Copperwood deposit is a stratabound copper sulfide (chalcopyrite) deposit that occurs about 30 km southwest of the White Pine deposit and is also hosted by the Nonesuch Shale. The deposit is on average 2.5m thick with measured, indicated and inferred resources at 33 million metric tonnes averaging 1.60 % Cu and 4.1 ppm Ag for contained metal of 1.165 billion lbs of Cu and 4.32 million oz of Ag (Bornhorst and Williams, 2013).
Fissure-hosted Copper Sulfide Vein Deposits - Copper sulfide vein deposits occur principally in two areas: 1) near the tip of Keweenaw Peninsula in Michigan, and 2) along Mamainse Point, Ontario (Nicholson et al., 1992). These copper sulfide occur as veins crosscutting the volcanic rocks as well as as stratabound deposits in amygdular flowtops. Chalcocite is the most abundant sulfide, followed by bornite and chalcopyrite. Veins on Keweenaw Peninsula are associated with weak alteration as compared to veins on Mamainse Point which show intense silicification and argillic and propylitic alteration (Nicholson et al., 1992). Vein deposits on Keweenaw Peninsula have been estimated to contain about 6.4 million metric tons of ore with an average grade of 2.3% Cu (Anonymous, 1989). On Mamainse Point, veins mined from the Coppercorp mine yielded about 1.1 million metric tons of ore averaging 1.46% Cu (Nicholson et al., 1992).

Polymetallic Vein Deposits - Silver-dominated, polymetallic quartz-carbonate veins are prevalent in the Thunder Bay area where historically almost 5 million dollars worth of silver ore has been produced since 1846 (Mudrey and Morey, 1972; Franklin et al., 1986; Kissin, 1992; Smyk and Franklin, 2007). The veins typically occur in the vicinity of contacts between Paleoproterozoic sedimentary units (usually Rove Formation shale) and Logan diabase sills. In addition to native silver and acanthite, the veins include a nickel-cobalt sulpharsenide suite of minerals as well as base metal sulfides and gangue minerals of quartz, carbonate, fluorite, and barite. The regional focus of the veins occur in or near crustal-scale listric faults associated with MCR extension that were reversed during late stage compression (Fig 8f; Smyk and Franklin, 2007).

Another type of polymetallic hydrothermal mineralization occurring in the Thunder Bay area is lead-zinc-barite veins that may also include amethystine quartz and uraninite (Franklin and Mitchell, 1977; Smyley and Franklin, 2007). These veins typically occur in the vicinity of the unconformity between the Sibley Group sedimentary rocks and the Archean basement. Uraninite alone in quartz veins and vein breccias with hematite and pyrite are also commonly found in the Archean basement near unconformities (Smyk and Franklin, 2007).

The rift-related hydrothermal deposits can be related to a regional model that includes heating of basinal brines, leaching of metals, and movement of fluids upsection (Nicholson et al., 1992; Swenson et al., 2004; Smyk and Franklin, 2007; Brown, 2006, 2008). With more than 2 million km$^3$ of mafic magma erupted in the rift and a comparable volume of mafic intrusions inferred beneath the rift, a ready and structurally confined supply of mafic source rocks were available for leaching of metals by basinal brines. These brines were heated by a steep geothermal gradient that resulted from the melting and underplating of magma derived from the mantle plume. Hydrothermal deposits were emplaced at least 30-40 m.y. after rift magmatism and extension ceased. This time lag may reflect either the time required to heat deeply buried rocks and fluid within the rift, or may be due to timing of post-rift compression that may have provided the driving mechanism for explosion of hydrothermal fluids from deep portions of the rift. Recently, Brown (2008) suggests that the focusing of ascending copper-rich brines into a narrow segment of Portage Lake strata along a 45-km-long stretch of the Keweenaw Peninsula may be attributed to upward thrusting on the Keweenaw fault during closure of the MCR, forming anomalously hot, steeply dipping aquifers on the Keweenaw promontory, and to the development of a single, dominant thermal plume within the incipiently buoyant brine at the scale of the mine district.
Magmatic Deposits

The main types of magmatic ore deposits associated with the Midcontinent Rift include: 1) low-grade Cu-Ni-PGE sulfide deposit hosted by gabbroic to troctolitic rocks occurring in the contact zones of Duluth Complex, Coldwell Complex, and other smaller gabbroic intrusions; 2) stratiform PGE “reef” intervals in layered mafic intrusions, 3) high-grade Ni-Cu-PGE sulfide deposits hosted by ultramafic rocks in small ultramafic to mafic intrusions (“conduit-type” magmatic sulfide deposits of Ripley and Lee, 2012); 4) Ti-Fe(-V) oxide-rich ultramafic intrusions in the Duluth Complex; 5) U-REE in small carbonatites cutting Archean rocks; and 6) Cu (Mo)-bearing breccia pipes resulting from local hydrothermal activity around small felsic intrusions (Fig. 10). The ages of the magmatic deposits span the entire range of magmatic activity in the rift from 1115-1086 Ma.

![Magmatic Deposits Diagram](image)

**Figure 10.** Occurrence of magmatic ore deposits associated with the Midcontinent Rift in the Lake Superior region (modified from Nicholson et al., 1992).

**Cu-Ni-PGE Sulfide Deposits at Contacts of Mafic Intrusions** - The copper-nickel sulfide mineralization of the basal portion of the Duluth Complex in Minnesota has been delineated along a 50 kilometer-long belt southeast of Ely, Minnesota (Fig. 7). Exploration of this mineralization, which has been ongoing
since 1950, has delineated 12 areas of significant grade to be classified as deposits (Hauck et al., 1997; Severson and Miller, 2002). Estimates of the amount of ore (defined as containing 0.1 Cu equivalent) in this belt are as great as 7 billion metric tons with average grades running 0.66% Cu and 0.2% Ni (Listerud and Meineke, 1977; Eckstrand and Hulbert, 2007; Peterson, 2010). The discovery of significant precious metal (Pd+Pt+Au) enrichment in the mid-1980s (Sabelin et al., 1986; Morton and Hauck, 1987), the Duluth Complex ores have come to be recognized as a significant PGE resource as well (Ripley, 1990; Mogessie and Saini-Eidukat, 1992; Ripley and Chryssoulis, 1994; Theriault et al., 1997; Hauck et al., 1997, Severson and Hauck, 2003, Peterson, 2010). Although low in grade, the large tonnage of ore makes the contained metal content of the Duluth Complex deposits world class. Compared to other magmatic ore deposits, Eckstrand and Hulbert (2007) estimated that the Duluth Complex ores rank first in contained copper (~40 billion pounds), comparable to Noril’sk (Fig. 11). They rank third behind Sudbury and Noril’sk in contained nickel and rank fourth behind Bushveld, Noril’sk, and the Great Dyke in Pd+Pt+Au. A resource estimate in December of 2012 indicates that the Maturi deposit alone hosts about one-third of all Duluth Complex resources (13.7 billion lbs copper, 4.4 billion lbs nickel, and 21.2 million oz. of PGE).

The Cu-Ni mineralization occurring at or near the base of the Duluth Complex is hosted mostly by troctolite intruded between slightly older anorthositic series units and the country rocks composed of Paleoproterozoic sedimentary rocks (shale, greywacke, iron formation) and Archean granitoids. Sulfide mineralization consists of mostly pyrrhotite, chalcopyrite, cubanite and minor pentlandite, generally occurring as disseminated grains among silicate phases in the troctolite, but also as veinlets, inclusions in silicates, intergrowths with hydrous minerals, and as rare massive sulfide segregations (Weiblen and Morey, 1976; Foose and Weiblen, 1986; Hauck et al., 1997; Severson and Miller, 2002). Stable and radiogenic isotopic data imply that the copper-nickel mineralization resulted from the interaction of the metal-bearing intruding magma and sulfur-rich fluids derived from desulfurization and dehydration of country rocks and was accompanied by at least some local partial melting and assimilation (Ripley, 1981, 1986; Lee and Ripley, 1996; Ripley et al., 1998; Ripley et al., 2001; Ripley et al., 2008).

Similar contamination-induced basal mineralization occurs in other subvolcanic intrusions in the MCR. These include the Great Lakes Nickel deposit in the Crystal Lake gabbro near the US-Canadian border (Eckstrand et al., 1989), the Mineral Lake Intrusion associated with the Mellen Complex in northwestern Wisconsin (Bakheit, 1981), and the Marathon deposit in eastern gabbro phase of the Coldwell Complex (Good and Crocket, 1994; Good et al., 2010). The Crystal Lake gabbro was emplaced into the Paleoproterozoic Rove Formation just north of the basal Duluth Complex (Fig. 3). The Great Lakes Nickel deposit has a historic (1974) indicated resources of 45,623.00 tons grading 0.344% Cu, 0.183% Ni, 0.0043 oz/ton Pt, and 0.021 oz/ton (Smyk and Franklin, 2007), though a renewed evaluation of the deposit is expected after the property was acquired by Rio Tinto (CNW news release, Nov., 2011). Advanced exploration and resource evaluation is currently being conducted on the Coldwell Complex’s Marathon deposit, which in 2010 was characterized as having Marathon’s optimized proven and probable reserve of 91.45 million tonnes grading 0.832 g/t Pd, 0.237 g/t Pt, 0.085 g/t Au, 0.247% Cu and 1.44 g/t Ag, and containing 2.44 million ounces of Pd, 696,000 ounces of Pt, 251,000 ounces of Au, 497 million lbs of Cu and 4.23 million ounces of Ag (Marathon PGM Corporation news release, Jan., 2010).
Stratiform PGE “Reef” Deposits - Economic concentrations of platinum group elements (PGEs) in meter-thick, stratiform, sulfide-bearing horizons (PGE reefs) have long been known to be associated with ultramafic-mafic layered intrusions such as the Bushveld and Stillwater complexes (Naldrett, 1993), typically occurring near the transition from ultramafic to mafic rocks. The discoveries of stratiform precious metal mineralization in the Skaergaard intrusion and related bodies of East Greenland (Bird and others, 1991; Aranson and others, 1997; Andersen and others, 1998; Andersen, 2006) demonstrated that PGE reefs may also exist in tholeiitic mafic layered intrusions. Stratiform PGE mineralization in well-differentiated tholeiitic intrusions are similar to classic PGE reef deposits hosted by ultramafic-mafic complexes, such as Bushveld and Stillwater complexes, in that they occur as sulfide-poor (<1 wt.%), PGE-rich intervals that are meters in thickness and are conformable with igneous layering. Stratiform PGE mineralization in tholeiitic intrusions, termed Skaergaard-type PGE mineralization by Prendergast (2000), differs from the classic PGE reefs, however, by being: 1) exclusively associated with mantle plume-influenced, continental rift environments; 2) of Middle Proterozoic age or younger, 3) associated with aluminous, olivine tholeiitic parent magma compositions that experience Fenner-type crystallization differentiation; 4) hosted by ferrogabbroic cumulate rocks, 5) associated with Cu-rich, Ni-poor sulfide, and 6) associated with significant Au that is stratigraphically offset above peak PGE concentrations (Miller and Severson, 2002b). Whereas there is considerable disagreement about how classic PGE reefs
formed (Cawthorn, 1998), most believe that Skaergaard-type reefs are orthomagmatic, i.e., they formed by the saturation, exsolution and settling of sulfide melt from silicate magma. The presence of many well differentiated layered intrusions of tholeiitic composition associated with the 1.1 Ga Midcontinent suggests that it is fertile ground for exploration for this type of mineralization.

Recognizing the remarkable similarities in the closed-system crystallization histories of the Skaergaard intrusion and the Sonju Lake intrusion (SLI) of the Beaver Bay Complex in northeastern Minnesota, Miller (1999) conducted a chemo-stratigraphic study of the SLI to determine if it may contain a Skaergaard-type reef. Elevated Pd and Pt concentrations (50-400 ppb) were discovered within an 80 meter thick interval hosted by oxide gabbro cumulates and situated stratigraphically below an abrupt increase in Cu (100 - 600 ppm). In 2002, Franconia Minerals drilled three cores through the PGE reef and supported a petrographic, lithochemical, and mineral chemical study by Greg Joslin for his MS thesis. Joslin (2004) showed that anomalous concentrations of Pd and Pt occurred over an 85-meter-thick interval and that peak concentrations were cyclical, offset from each other and from the abrupt increase in Cu, and correlative among the three cores (Fig. 12). The detailed chemostratigraphy also showed that gold was concentrated at the abrupt increase in Cu (Cu-Au break). Joslin concluded Cu and precious metal mineralization was generated by sulfide saturation that was passively triggered by closed-system fractional crystallization of the SLI parent magma. He further concluded that the Pt and Pd concentrations reflected primary mineralization, whereas the Cu and Au break represented a sulfide dissolution front created by the migration of deuteric fluids through the mineralized zone. The broad thickness of PGE mineralization is thought to result from the slow settling of small amounts (~0.1 wt.%.) of sulfide liquid that would be generated from a passively saturated tholeiitic magma.

![Figure 12](image_url)

**Figure 12.** Stratigraphic variations in concentrations of Cu, Au, Pt, and Pd across the Precious Metal Zone of the Sonju Lake Intrusion observed in three Franconia drill cores. The core are correlated at the Cu-Au break. However, Miller (2011) argues that complex Pt and Pd peaks are primary orthomagmatic signatures of mineralization and that the Cu-Au peak is a secondary feature representing a sulfide dissolution front. Cu values in ppm, Au, Pt, and Pd values in ppb. From Joslin (2004).
Another MCR layered intrusion that shows evidence of a stratiform PGE reef is the Layered Series at Duluth (DLS; Miller, 2011). This 4-km-thick sheet-like body, which is the type layered intrusion of the Duluth Complex, is well differentiated, but displays cyclical phase and cryptic layering that indicates that it was open to multiple episodes of magma venting and recharge. Chemostratigraphic variations in chalcophile elements through the DLS indicates that sulfide saturation likely occurred in the medial section of the body where troctolitic cumulates begin to cyclically grade into gabbroic cumulates, a section termed the Cyclic Zone. Given the lack of cyclical cryptic layering attending the phase layering of the Cyclic Zone, Miller (2011) interpreted this phase layering as largely caused by decompression attending magma venting under low lithostatic pressures. He further speculated that under water saturated conditions, decompression may have also triggered sulfide saturation and PGE reef mineraliation in the lower part of the cyclic zone. If such mineralization is found, its formation by more dynamic processes may result in a more economic reef by virtue of its being thinner and higher grade.

Stratiform PGE mineralization in mid- to upper levels of mafic layered intrusions have been reported in other MCR-related layered intrusions (Seagull – Heggie, 2005; Partridge River - Geerts, 1991, 1994; South Kawishiwi – Severson, 1994; BIC – Foley, 2011; Tamarack – Goldner, 2011; Echo Lake – Billard, 2003). Of these, only the BIC occurrence, which is hosted in oxide gabbro, appears to be a Skaergaard-type PGE reef formed by sulfide saturation passively triggered by fractional crystallization. Most of the other reef occurrences are what Miller and Severson (2002b) termed stratabound PGE mineralization because they are commonly associated with a particular rock unit, usually olivine cumulates that seem to mark a recharge event into the magma chamber (Severson, 1994). Other ways that stratabound reefs differ from “Skaergaard-type reefs” is that sulfides are not as depleted in Ni and sulfide typically becomes undersaturated in the overlying unit. With most uncontaminated primitive tholeiitic magmas being initially undersaturated in sulfide, magma recharge in and of itself should not be able to cause sulfide saturation. The fact that most of these ultramafic-hosted PGE reef occurrences are associated with intrusions that have significant basal contact sulfide mineralization, it seems likely that stratabound reef mineralization is due to sulfide contamination as the recharging magmas pass through the basal mineralized zones or sulfide-enriched conduits. That sulfide eventually becomes undersaturated may indicate that only the leading edge of the recharging magma becomes oversaturated.

Ni-Cu-PGE Sulfide Deposits in Small Ultramafic Intrusions – Clearly one of the most stimulating mineral discoveries in the past 15 years has been the recognition of high-grade Ni-Cu-PGE mineralization associated with small ultramafic-mafic intrusions (“conduit-type” magmatic sulfide deposits; Ripley and Lee, 2011) emplaced during the initiation and early stages of MCR magmatism. The currently identified intrusions include Kitto, Hele, Seagull, Disraeli and Current Lake intrusions and the Jackfish Island, Shilabeer, and Riverdale sills in the Lake Nipigon-Thunder Bay, Ontario area; the Eagle, BIC, and Roland Lake intrusions in upper Michigan; and the Tamarack intrusion of east central Minnesota (Fig. 3). Although several of these ultramafic intrusions were identified decades ago (e.g, Eagle was known as the Yellow Dog peridotite, Klasner et al., 1979; Kitto and Disraeli were identified as picritic intrusions by Sutcliffe, 1987; the unexposed Tamarack intrusion was known from one shallow drill core acquired by the Minnesota Geological Survey, Southwick et al., 1986), the presence of significant mineralization in the basal contact zones of many of these intrusions was not discovered until about 15 years ago when exploration drilling was conducted. Summarized here are brief descriptions of the five best studied intrusions to date – Seagull, Current Lake, Eagle, BIC, and Tamarack.
The first discovery was made of the Seagull intrusion by exploration drilling of aeromagnetic anomalies southwest of Lake Nipigon in 1997 (Smyk and Franklin, 2007). A detailed petrologic study of several drill cores by Heggie (2005) shows the lopolithic intrusion to be composed of a 800 m-thick keel comprising olivine cumulates (dunite, peridotite, lherzolite) overlain by a 100 m-thick sheet of feldspathic pyroxenite to gabbro. Middleton and Heggie (2005) reported a basal contact zone of disseminated sulfide with grades up to 0.35% Cu, 0.25% Ni, and 3.6 ppm Pt+Pd (~1:1 ratio). Several PGE-rich stratiform horizons of finely disseminated sulfide in 5 meter-thick intervals occur between 100-200 meters above the basal contact and run as high as 0.68% Cu, 0.36% Ni, 5.5ppm PGE. Heggie (2005) interpreted these upper stratiform horizons to have formed by recharge into the chamber by S-contaminated magmas.

The Current Lake intrusion north of Thunder Bay, Ontario was discovered in 2006 by Magma Metals Ltd. when angular peridotite boulders enriched with Ni-Cu-PGE sulfide were traced up-ice to a prominent linear aeromagnetic anomaly. An extensive drilling program over the past six years has recovered over 145,000m of core which in 2009 defined an indicated resource of 4.6 Mt grading 1.35 g/t Pt, 1.27 g/t Pd, 0.32% Cu and 0.22% Ni (MacTavish and Smyk, 2010). A May 2012 press release reports an indicated resource of 10.3 Mt with a platinum equivalent grade of 2.4 g/t. The extensive drilling shows the mineralized intrusion to be a sub-horizontal, 30-50 m wide by 30-70 m thick chonolith that gradually deepens and widens to the south (Goodgame et al., 2010). Disseminated mineralization occurs throughout the peridotitic intrusion, which is dominantly composed of olivine cumulates with interstitial augite and plagioclase. An inclusion-rich quartz leucogabbro commonly occurs at the margins of the mineralized peridotite and is interpreted to represent a precursor intrusion that has been strongly contaminated and hydrothermally altered (Chaffee et al., 2012).

By far the richest Ni-Cu-PGE mineralization discovered among the MCR ultramafic-mafic intrusions is associated with the Eagle Deposit of Upper Michigan. Discovered in 2002 by Kennecott Exploration, massive to semi-massive sulfide hosted by peridotitic to olivine melagabbroic rocks occurring in a narrow funnel-shaped intrusion within Paleoproterozoic black shales (Ware et al., 2009; Ding et al., 2010). A U-Pb age of 1107.2 ± 5.7 Ma for badellyites has been reported by Ding et al. (2010). Its elliptical areal extent of the intrusion is about 480 m long by 100-200 m wide. Eagle East is a similarly shaped, though less richly mineralized intrusion that occurs 0.6 kilometers east of the Eagle body. A 2009 Kennecott report gave a resource estimate for Eagle of 4.05 million tons with an average grade of 3.57% Ni, 2.9% Cu, 0.10% Co, 0.28 ppm Au, 0.73 ppm Pt, and 0.47 ppm Pd (Ding et al., 2010). Geochemical and mineral chemical studies by Ding et al. (2010) concluded that the intrusion formed in a dynamic conduit setting from at least three magma pulses which were olivine-phyric and sulfide-oversaturated due to country rock contamination.

Occurring in a similar geologic setting as Eagle, but 45 kilometers to the east (Fig. 3), is the small broadly funnel-shaped BIC (Bovine igneous complex) intrusion (Rossell, 2008; Foley, 2011; Foley et al., this issue). Unlike other MCR ultramafic intrusions, the BIC intrusion is relatively well exposed in a 1 x 0.5 km hillock, though mineralization is not evident at surface. Mineralization near the basal contact of the intrusion was discovered in drill core by Kennecott in 1995 though this and subsequent drilling has yet to reveal economic mineralization. Rossell (2008) reported one 16.47m intersection averaging 0.88%Cu, 1.00%Ni, 0.679ppm Pt, 0.991ppm Pd and 0.104ppm Au. A recent mapping and petrologic study (Foley, 2010; Foley et al., this issue) shows the intrusion to composes of two differentiated cycles of cumulates: 1) Ol→Cpx+Ol, 2) Ol→Cpx+Ol→Cpx+Ox+Ol→Pl+Cpx+Ox→Pl+Cpx+Ox+Ap. Foley (2010) interpreted these cycles to indicate to main pulses of a high-Mg tholeiitic magma that underwent fractional crystallization. Each pulse produced basal contact sulfide mineralization due to country rock contamination.
contamination attending initial emplacement and the second cycle also produced sulfide-poor, stratiform (reef-style) PGE-enriched mineralization where oxide appears as a cumulus phase.

The Tamarack intrusion is an unexposed mineralized ultramafic intrusion located about 50 miles west of Duluth, Minnesota. After shallow drilling by the Minnesota Geological Survey discovered unmineralized ultramafic rock generating a linear aeromagnetic anomaly in the Paleooproterozoic Animikie Basin (Southwick et al., 1996), Kennecott Exploration began exploration drilling of the anomaly in 2001 and soon encountered significant Ni-Cu-PGE mineralization. Like Eagle and BIC, the Tamarack intrusion was emplaced into pyritic Paleooproterozoic black slates during the early magmatic stage of the MCR (U-Pb baddeleyite age of 1105.6 ± 1.3 Ma; Goldner, 2011). Taranovic et al. report δ34S values between 0.8 and 2.8 indicating up to 50% contamination by external sulfur. Drilling and geophysical data indicate that the Tamarack intrusion has a tadpole-like shape that is about 13 km long and is between 1 and 4 km. The narrow tail area of the intrusion, which is the site of greatest exploration drilling, is composed of exclusively of lherzolitic rock types (cumulus Ol with interstitial Cpx, Opx, and Pl), which Goldner (2011) interprets to have formed in two pulses. The wider “body” area at the southeastern end of the intrusion is composed of a wider variety of rock types ranging from lherzolite to granophyric gabbronorite that Goldner (2011) concludes formed by closed system fractional crystallization. In a March 2009 press release, an estimated reserve of 9-11mt was reported with a grade range of 1.0-1.1 % Ni and 0.6-0.7% Cu, but a full resource estimate has not been released.

**Ti-Fe(-V) Oxide Deposits** - High concentrations of vanadium-rich ilmenite and titanomagnetite minerals occur in many gabbroic intrusions related to the MCR. In the Duluth Complex, Hauck et al. (1997) identified three distinct occurrences: 1) banded or layered, oxide-rich, meta-sedimentary inclusions in mafic and ultramafic rocks; 2) banded or layered oxide segregations (cumulates) in mafic rocks; and 3) discordant oxide-bearing ultramafic intrusions (OUIs) with semi-massive to massive oxide zones. Titaniferous iron ores were first discovered in the Duluth Complex around 1867, at about the same time as the initial discovery of the Mesabi Range iron ores (Winchell, 1897). The earliest discoveries took place along the northern margin of the Complex in Cook County, MN. Grout (1949-50) estimated that along the northern margin there are 81.6 million tons of low-grade titaniferous magnetite ore (in 14 bodies) with an average grade of 12-14% TiO₂ (Hauck and others, 1997b). Oxide mineralization is also associated with late plug-like oxide ultramafic intrusions (OUI) along the western margin of the Duluth Complex (Severson and Hauck, 1990; Severson, 1995). The OUIs were initially discovered by drilling magnetic highs during Cu-Ni exploration. Listerud and Meineke (1977) estimate that 220 million tons of oxide material, with >10% TiO₂, are present in at least three of the OUI bodies. However, an additional nine areas are known to contain titaniferous iron ores and are not included in their original estimate (Severson, 1995). A recently released resource estimate for two OUI bodies currently being explored give indicated resources of 58.1Mt @ 16.6% TiO₂, 18.8% Fe₂O₃ and inferred resources of 65.3Mt @ 16.4% TiO₂, 19.4% Fe₂O₃ for the Longnose deposit and inferred resources of 45.1Mt @ 15.0% TiO₂, 14.74% Fe₂O₃ for the TiTac deposit (formerly the Section 23 occurrence; Caredero Resources Inc, news release, Jan, 2012).

Titaniferous oxide concentrations have also been recognized in MRS gabbroic intrusions in northern Wisconsin (Nicholson et al., 1992). The Round Lake intrusion, although not exposed, is inferred from geophysical data and limited drilling to be at least 8 km long and less than 1.5 km wide (Stuhr and Cameron, 1976). Drill core shows the intrusion to be layered and consist of magnetite-troctolite, magnetite, anorthositic olivine gabbro, and mafic pegmatite. Titaniferous magnetite is present throughout the intrusion but is concentrated in an oxide-rich core.
**U-REE Mineralization** - Intrusions of carbonatite and alkalic complexes that host U-REE mineralization are presently known only north of Lake Superior along the Kapuskasing structural zone and along a north-trending zone north of the Coldwell Complex (Fig. 3; Weiblen, 1982; Sage, 1987, 1988; Nicholson et al., 1992; Smyk and Franklin, 2007). MCR intrusions associated with U-REE mineralization include the alkaline phases of the Coldwell Complex (1108 Ma; Heaman and Machado, 1992), the Killala Lake alkali complex (Sage, 1988), the Prairie Lake carbonatite complex (~1030 Ma; Bell and Blenkinsop, 1987) and the Firesand River alkalic complex (1060 Ma; Bell and Blenkinsop, 1987). A crustal lineament defines a northerly trend that connects the carbonatite-alkalic complexes of Coldwell, Killala Lake, and Chipman Lake (Fig. 3). The Prairie Lake carbonatite lies at the intersection of two well-defined lineaments, including one that connects the Prairie Lake to the Killala Lake Complex (Sage, 1987).

Recent interest in rare earth and related elements has led to active exploration in the Prairie Lake carbonatite and the Coldwell Complex, Ontario. The Prairie Lake deposit is among the top 10 carbonatite-hosted niobium deposits in the world, although its resources have not yet been fully defined. Other elements of interest include tantalum (Ta2O5), uranium (U3O8) and rare earth elements (REE) (Nuinsco Resources Limited, http://www.nuinsco.ca/projects/prairie-lake/ as of May 6, 2012). Exploration for rare earth elements in the Coldwell Complex have focused on niobium, zirconium, yttrium, and rare earth elements (Rare Earth Metals Inc., http://www.rareearthmetals.ca/article/coldwell-complex-169.asp as of May 6, 2012).

**Cu (Mo)-bearing Breccia Pipes** – Disseminated Cu and Cu-Mo mineralization occurs in four breccia pipes in the Tribag area on the eastern side of Lake Superior, near Mamainse Point, Ontario (Fig. 3). These oval breccia pipes occur within Archean metavolcanic basement along a granite-greenstone contact, and within approximately 6 km of the contact of the Archean rocks with overlying Keweenawan basalts and sedimentary rocks (Blecha, 1974; Norman and Sawkins, 1985). Numerous basaltic and felsic dikes of probable Keweenawan age intrude the highly fractured Archean basement and many predate brecciation (Norman and Sawkins, 1985). The breccia pipes have been dated at 1055 ± 35 Ma based on a K-Ar isotopic age determination for muscovite from altered rocks that contain chalcopyrite, quartz, and carbonate (Roscoe, 1965).

The sulfide deposits were discovered in 1954 with additional exploration and development work carried out in the 1960's. Two breccias pipes were mined from 1967 until 1974, during which time about 35.2 million lbs (16,000 mt) of copper were produced from 6.4 million tons (5.8 million mt) of ore averaging 2.75% Cu (Blecha, 1974; Norman and Sawkins, 1985). Sulfide mineralization in the Tribag deposits consists of chalcopyrite and pyrite with minor sphalerite, galena, tetrahedrite, and molybdenite. Blecha (1974) also reported small amounts of recoverable silver and gold.

**Areas of Future Research**

In December, 2010, an informal working group of academic, government, and industry geoscientists met in Duluth to discuss where future research should be directed to improve our understanding of the geology, mineralization and tectonomagmatic evolution of the MCR. Action items for future research put forth during those discussions provide a fitting way to conclude this summary and review.

- Develop and manage a digital GIS compilation of geological, structural, lithologic, lithochemical, mineral chemical, geochronologic, physical property, and mineral deposit data for the entirety of the exposed MCR. Such a compilation has been informally maintained by the US Geological Survey, the Minnesota Geological Survey, and the Ontario Geological Survey for almost two
decades. A preliminary release of some of this database is expected in the near future and will provide an invaluable foundation for future studies and exploration of the MCR.

- Continue to conduct detailed mapping throughout the MCR where appropriate. Many areas of good bedrock exposure within the MCR still remain to be mapped in detail (1:20,000-50,000). With the recent discovery of mineralized ultramafic intrusions throughout the poorly mapped Quetico subprovince of Ontario, detailed mapping is particularly needed here.

- Acquire (and re-acquire) more high-precision U-Pb dates from MCR volcanic and intrusive rocks to better establish temporal correlations between volcanic sequences and between volcanics and intrusive units; to better constrain rates of emplacement and eruption rates; to verify the accuracy of seemingly anomalous ages; and to establish the areal extent of MCR magmatism. Inter-laboratory comparisons should be run in order to establish confidence in results. Additionally, establishing good field relationships, to the extent possible, is necessary before acquiring samples for radiometric dating. Two groups that will benefit from detailed age dating are: 1) Mamainse Point Formation in Ontario and 2) the Powdermill Group in Michigan and Wisconsin.

- Accumulate more complete and higher resolution chemostratigraphic databases through the various volcanic sequences. An evaluation of the chalcophile element chemostratigraphy of volcanic sequences (tied to accurate chronologic data) has elsewhere shown promise for identifying potential mineralized intrusions at depth (e.g., Lightfoot and Keays, 2005; Keays and Lightfoot, 2006).

- Conduct geochemical modeling of volcanic rocks in order to understand the magmatic sources and processes that generate the compositional diversity of MCR magmas. With geophysical models and geologic observations indicating magmatic staging occurring at various depths in the crust, it would be interesting to understand the extent to which that diversity is generated by high pressure vs. low pressure fractional crystallization. Other petrochemical questions include the origin of high-Ti vs. low-Ti basalts and the significance of variable Nb-Ta anomalies.

- Within mafic layered intrusions of the MCR, acquire high resolution PGE assay data (<1ppb accuracy) in order to assess the potential for PGE reef deposits by monitoring the stratigraphic variation in mineralization indicators such as the Cu/Pd ratio (Barnes and Lightfoot, 2005).

- Acquire new high resolution geophysical surveys and physical properties data (e.g. specific gravity, magnetic susceptibility, polarity) for MCR rocks and country rocks. Particularly useful surveys would include high resolution aeromagnetic surveys (<200m spacing) in areas flanking the MCR (e.g. Animikie Basin, Baraga Basin, Archean basement around Thunder Bay); airborne gravity surveys; depth to bedrock surveys using newly developed passive source seismometers; and high precision paleomagnetic surveys as recently conducted by Hysell-Swanson et al. (2009; this volume). Evaluation of the recent Earthscope wide array passive seismic survey data will likely lead to a better understanding of the deeper structure and composition of the crust, especially the character of the mafic underplated keel inferred by other geophysical models.

- To identify prospective areas under a thick glacial cover, conduct detailed surficial mapping over and down-ice of the MCR and evaluate regional till sample surveys for metallo-magmatic indicator minerals - Cr-spinels, Fe-Ti oxides, sulfides, olivine (analyzed for Fo and Ni%)
- Characterize the effects of deep weathering on the chemistry and magnetic properties of MCR intrusive rocks. Understanding the latter effect would help to better interpret aeromagnetic data, which is critical to making geological interpretations in areas of significant glacial cover.

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FIELD TRIP 1
Caledonia Mine, Keweenaw Peninsula Native Copper
District, Ontonagon County, Michigan

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This field trip guide was originally published by the Institute on Lake Superior Geology,
Directions: Leave downtown Houghton and head south on M-26 towards South Range. Stay on M-26 (highway turns into M-38 past the Mass City turnoff) for 39 miles past Greenland (Pat’s Auto & Sports Center) to Ridge Road. Turn left (south) on Ridge Road approximately 1 mile to Caledonia Rd. Drive southwest 1.7 miles (2.7 km) to the Caledonia Mine. The Caledonia mine is privately owned and permission is required to enter this property [UTM 5179684N 160338022E (NAD27 CONUS)]

The Caledonia Mine, surface and underground, is strictly private property. Permission is required to enter the property.

Introduction

The Caledonia Mine is part of the Keweenaw Peninsula native copper district of the western Upper Peninsula of Michigan (Fig. 1.1). The Caledonia Mine is located in the Greenland-Mass subdistrict about 40 km southwest of the Baltic Mine, the southernmost major native copper mine (Fig. 1.2). In total the mines on the Evergreen succession produced about 73 million lbs of copper at grades ranging from 0.5 to 1.25 % (Weege and Pollock, 1971) and, as compared to total district production of 11,000 million lbs of copper, this subdistrict was a minor producer. The largest producer among the Greenland-Mass subdistrict mines was the Mass Mine which produced about 51 million lb of refined copper from 1851 to 1923 (Butler and Burbank, 1929). The Adventure Mine produced about 11 million lb of copper. Despite its low production of copper, the geologic characteristics of the Greenland-Mass subdistrict deposits are typical of the native copper deposits elsewhere in the Keweenaw Peninsula. Since native copper mining in the Keweenaw Peninsula ceased in 1968, underground access to observe or study the native copper deposits is limited today to four mines, two of which are in the Greenland-Mass subdistrict (Caledonia and Adventure Mines). The Caledonia Mine is one of the few remaining localities where a typical native copper ore body hosted by the top of a basalt lava flow can be observed up close underground.

This field trip guide relies on existing publications by Bornhorst and Whiteman (1992 and 1995) and Bornhorst and Barron (2011). The geologic and human history overview is summarized from Bornhorst and Lankton (2009). Since professional and collector oriented underground field trips to the Caledonia Mine are common, the introductory explanations have been expanded to provide a more readily stand alone field trip guide. Underground, the Caledonia Mine is relatively dry and regular field boots are usually sufficient; hard hats and lights are required. The field trip involves an easy walk underground to observe the character of native copper mineralization in an adit and a drift that parallels the strike of the tabular native copper ore body (lode) that is hosted by the top of the Knowlton lava flow. The cross-cutting adit provides opportunity to observe the Knowlton lode in cross-section as well as to observe underlying lava flows of the Evergreen succession. An optional more difficult segment of the field trip involves climbing up into an underground stope on the Knowlton lode to observe the character of mineralization and to collect specimens. Specimens of native copper and associated minerals from hosted by rocks of the Caledonia Mine can be collected on the rock pile adjacent to the adit. The Caledonia Mine is owned and operated by Red Metal Minerals as an educational facility and to recover specimens for resale in the general public and mineral collector markets.
Regional Geologic and Human History Overview

The Keweenaw Peninsula is home to the largest known accumulation of native copper on the planet termed the Keweenaw Peninsula native copper district. The district is unique in comparison to copper mining districts elsewhere in that native copper comprises nearly all of the metallic minerals in the mined ore bodies. Approximately 11 billion pounds of refined copper from 380 million tons of ore were produced from native copper mines from 1845 to 1968 (Weege and Pollock, 1971). Small quantities of native silver occur with the native copper. Copper sulfides are uncommon in the Keweenaw Peninsula native copper district although chalcocite occurs in veinlets cutting the deposits (White, 1968). Near the tip of the Keweenaw Peninsula, there are several small unmined chalcocite-dominated deposits but their connection with the native copper deposits is uncertain (Maki and Bornhorst, 1999).

The native copper deposits of the Keweenaw Peninsula are hosted by rocks of the Mesoproterozoic Midcontinent Rift (MCR) (Figs. 1.1 and 1.2). The MCR is filled with more than 25 km of volcanic rocks and 8 km of clastic sedimentary rocks (Cannon et al., 1989 and 1993). This thick succession of rocks was emplaced between about 1.15 to 1.03 Ga (Cannon et al., 1989; Davis and Paces, 1990; Heaman et al., 2007). Volcanic rocks were erupted on land.
surface initially over a broad area above a mantle plume and later, were erupted from fissure volcanoes within the normal fault-bounded rift graben. The volcanic rocks erupted during this synrift phase of the MCR were predominantly subaerial tholeiitic flood basalt lava flows. The subaerial basalt lava flows have a top which is vesicular (amygdaloid) and/or brecciated (fragmental amygdaloid) underlain by a massive (vesicle-free) interior. The typical flow is 10 to 20 m thick. Minor gravels and sands were deposited on top of the lava flows during hiatuses in volcanic activity and today occur as red conglomerate and sandstone that are interbedded with the lava flows. After active rifting and volcanic activity ended, the rift basin continued to sag. Rivers carried gravels, sands, silts, and muds to fill this sagging rift basin, and with subsequent burial they were lithified into clastic sedimentary rocks which occupy the center portion of the rift today (Merk and Jirsa, 1982). Volcanic rocks crop out around the margin of the rift (Fig. 1.1).

The last and final phase of the MCR resulted from a regional compressional event due to collision of continental land mass along the eastern edge of North America at that time (Grenville Orogeny, Cannon, 1994). Compression inverted the rift-bounding normal faults into reverse faults as well as folding, faulting, and fracturing rift-filling volcanic and clastic sedimentary rocks. Native copper and related minerals were emplaced during this regional compressional event about 1.06 to 1.04 Ga (Bornhorst, 1997).

For roughly 500 million years, from about 1.0 Ga to 500 Ma, there were no geologic events recorded by rocks of the Upper Peninsula. During this time interval, erosion exposed the native copper deposits to the surface and downward percolating oxidizing groundwaters had access to alter the native copper (Bornhorst and Robinson, 2004). After being buried beneath Phanerozoic sedimentary rocks (500 Ma to 175 Ma) (Catacosinos and others 2001), Pleistocene continental glaciations removed all but a few outliers of these rocks from the Keweenaw Peninsula and exposed the native copper deposits at the surface.

Native people began exploiting native copper by ca. 7,000 years ago as the land surface of the Keweenaw Peninsula emerged above the retreating glacial lake levels. At first these prehistoric ancient miners likely found boulders of native copper (locally termed float copper) with their distinctive green weathered crust of malachite among the brown, gray, red, and white rocks. As they discovered the usefulness of native copper, they moved on to mining of bedrock. Because of the scars these early exploits left on the landscape, most mines of the Keweenaw Peninsula were rediscovered later including the Caledonia and those nearby. The first major mining rush in North America was started by Douglass Houghton through his report to the Michigan legislature in 1841. The Cliff Mine became the first profitable mine in the district in 1849. The Minesota Mine, in the southwest cluster near Caledonia Mine (Fig. 1.3) became profitable soon after the Cliff. In 1880, copper production from native copper mines of the Keweenaw Peninsula accounted for up to 80% of the nation’s copper production. The peak copper production occurred in 1916 at 267 million pounds with mining ending in 1968. The Keweenaw National Historical Park was created in 1992 to preserve and interpret the historical importance of native copper mining to the history of the U.S.

**Native Copper Deposits of the Keweenaw Peninsula**

The pre-mining geologic resource of the Mesoproterozoic Keweenaw Peninsula native copper district totaled about 20 billion lbs of Cu (Bornhorst and Barron, 2011). Most of the native copper in the district is hosted in the permeable and porous brecciated and amygdaloidal lava
flow tops (~58.5% of production) and interflow conglomerate-sandstone horizons (~39.5% of production). The ore is "sandwiched" above and below between barren massive basalt that lacks permeability and porosity and is geometrically found in tabular bodies between 3 and 5 m thick that have the same orientation as surrounding host rocks, i.e., stratiform lode. The typical lode has a lateral extent of 1.5 to 11 km and extends down-dip 1.5 to 2.6 km (Butler and Burbank, 1929; White, 1968). Native copper fills open spaces from a few cm across (e.g., vesicle-fillings) to small-to-moderately sized openings (e.g., space between lava flow top breccia fragments or between clasts in conglomerate) that contain native copper masses weighing up to several pounds and rarely weighing tons. A minor amount of native copper was produced, ~2%, from high-angle tabular veins that cut across the volcanic-dominated strata.

Native copper is closely associated with over 100 different minerals in the Keweenaw Peninsula although only about 25 of them are common. These minerals fill the same open spaces along with and instead of native copper (Butler and Burbank, 1929; Stoiber and Davidson, 1959; White, 1968). The suite of minerals is similar to those found where rocks have undergone very low to low grade burial metamorphism, < 300°C. Overall, higher temperature assemblages are spatially associated with the area of native copper deposits where the thermal anomaly was greatest because of focused hydrothermal fluid flow. In areas more distal to the deposits, the open spaces are filled with lower temperature assemblages. At any one location, there is a recognizable sequence in the precipitation of minerals from hydrothermal fluids due to changing hydrothermal fluid temperature and composition. The absolute age of the hydrothermal activity is coincident with the age of the regional compressional event at about 1.06 to 1.04 Ga (Bornhorst et al., 1988). The compressional event provided the plumbing system, faults/fractures, that facilitated movement of the hydrothermal fluids into the sites of future mineable deposits of native copper (Bornhorst, 1997).

![Figure 1.2 Bedrock geologic map of the western part of the Upper Peninsula of Michigan showing the location of Greenland-Mass subdistrict and the Caledonia Mine.](image-url)
The native copper mineralizing event was widespread throughout the exposed MCR (Fig. 1.1). Burial metamorphism at depth of rocks down-dip from the deposits was the likely source of the mineralizing hydrothermal fluids; small amounts of copper and other constituents were leached from the rift-filling basalt-dominated rocks. Subaerial eruption of the basalt lava flows likely resulted in the degassing of most of the contained sulfur leaving them sulfur poor. Thus, the hydrothermal fluids generated from them were low in sulfur and the movement of these fluids through the same sulfur poor rocks resulted in sites of ore deposition where host rocks were also sulfur poor. This low sulfur environment favored the deposition of native copper rather than copper sulfide. The heating of the volcanic rocks during burial probably reached a maximum millions of years after they were erupted and it was most likely the coincidence of increased fluids generated at this temperature maximum with the regional compressional event which played a critical role in providing the plumbing system necessary for producing the deposits (Bornhorst, 1997).

**Geology of the Evergreen Series**

The native copper mines in the Greenland-Mass subdistrict produced native copper from the tops of rift-filling lava flows that comprise the Evergreen succession within the Portage Lake Volcanics (Fig. 1.3 and 1.4). The Evergreen succession of basalt lava flows have a total thickness of about 210 m. The individual copper-rich lava flows within the succession were each informally named. From bottom to top the Evergreen succession consists of: the Evergreen flow: a 3 to 15 m thick plagioclase porphyritic otherwise aphanitic basalt lava flow; the Ogima flow, a 30 to 43 m thick slightly plagioclase glomerophyritic basalt lava flow; the Butler flow, a 15 to 27 m thick plagioclase glomerophyritic basalt lava flow; and a horizon of thin plagioclase glomeroporphryitic flows 75 to 90 m thick. This latter stratigraphic horizon of multiple flows includes the Mass flow. The South Knowlton flow overlies this horizon and is a plagioclase glomeroporphryitic lava flow up to 15 m thick and at the top of the Evergreen succession is the Knowlton flow, a 9 to 21 m thick plagioclase glomeroporphryitic lava flow (Calumet and Hecla, 1958). The volcanic rocks nearby underlying the Evergreen succession are ophitic and aphanitic basalt lava flows. The nearby overlying volcanic rocks are ophitic basalt lava flows. The Evergreen succession is stratigraphically at the level of the Isle Royale flow near Houghton.

The tops of these flows were productive over a strike length of about 5 km. Of the lava flows in the Evergreen succession, the Butler flow top yielded the most copper followed by the Evergreen and Knowlton flow tops which also yielded significant amounts of copper. Most of the Evergreen succession basalt lava flow tops are brecciated (fragmental amygdaloid) with considerable lateral (along strike) variation in the degree of brecciation and thickness. In some areas, thin lava flows lack brecciated tops and are simply vesicular (amygdaloid). In general, the best grades of copper occur where the brecciated flow top thicken. Secondary minerals in all of the flow tops are quite similar. Quartz, feldspar, pumpellyite, chlorite, calcite, and epidote are abundant minerals filling amygdules and spaces between breccia fragments. There is less abundant native silver, prehnite, datolite, and laumontite.

The Evergreen succession in the Greenland-Mass subdistrict dips about 45° NW towards Lake Superior and forms a local broad open anticlinal structural bend (Fig. 1.3). The largest mine, the Mass Mine, occurs near the maximum bend in this anticline. Faults with significant vertical displacement are uncommon as most have displacement of < 1 m. There are multiple veins in tension fractures that cut perpendicular across the lava flows in association with the anticline.
(Butler and Burbank, 1929). However, some veins are parallel to strike of the lava flows but dip in the opposite direction. In the stratigraphically equivalent Isle Royale lode, Broderick (1931) describes similar strike parallel veins which he interpreted to be feeders of ore fluid into the top of the lava flow.

Figure 1.3: Generalized bedrock geologic map of the Greenland-Mass subdistrict of the Keweenaw Peninsula Native Copper District showing the location of native copper mines. Geologic cross section shows the Evergreen Succession within the Portage Lake Volcanics; a lithostratigraphic column is given in Figure 4. Subdistrict bedrock geology and cross section modified from Whitlow (1974).
Figure 1.4: Stratigraphic position of the Evergreen succession that hosts native copper deposits of the Greenland-Mass subdistrict as compared to lithostratigraphic units of the Keweenaw Peninsula, Michigan. Units from the Powder Mill Group to the Jacobsville are all Mesoproterozoic in age and related to the Midcontinent Rift.

Geology of the Caledonia Mine

In the context of mines in the Keweenaw Peninsula native copper district, the Caledonia Mine was very small, producing only about 6.8 million lb of refined copper from the top of the Knowlton basalt lava flow (Knowlton lode), the youngest basalt lava flow of the Evergreen Series (Fig. 1.4). The near horizontal adit of the mine follows approximately along strike of the Knowlton lava flow where it connects with the Knowlton Mine (Fig. 1.5) and to where it connects to the stopes of the Mass Mine “C” shaft (not shown). At the Mass Mine, the stratigraphically lower Butler lava flow top was the principal focus of native copper mining. In the Greenland-Mass subdistrict the Butler lava flow top was developed for about 2000 m along strike and to a maximum depth of 300 m along dip. The most abundant secondary minerals in the Butler are quartz and calcite with slightly lesser amounts of K-feldspar and epidote. Prehnite and pumpellyite are usually much less abundant and chlorite is present in amounts < 1%. The Butler contains a high number of veins, usually they strike subparallel to the strike of the Butler lava flow top and have dips both similar to the dip of bedding and at a high angle to bedding (Butler and Burbank, 1929).

Figure 1.5. Map of the underground workings at the level of the Caledonia Mine entrance. The average grade of Cu is shown for the mined out areas of the Knowlton flow top. Map and Cu grade from Calumet and Hecla (1958).
In the Greenland-Mass subdistrict, the Knowlton flow top was developed for about 3000 m along strike and to a maximum depth of about 375 m. The Knowlton was the focus of native copper mining at the Caledonia Mine. The Knowlton lava flow top is a brecciated flow top or fragmental amygdaloid. Stopes at Caledonia were raised on the Knowlton lode upwards from the drift toward the topographic high of the Caledonia bluff (Fig. 1.6). The floor (footwall) of the stopes reflects the original depositional irregularities of the top of the underlying lava flow such as gentle flexures. The average thickness of the Knowlton lava flow top is about 2.5 m but locally it can thicken to around 6 m (Calumet and Hecla, 1958). In general, a thicker flow top results in better ore. While most of the ore occurs in the top of the Knowlton lava flow top, there are pockets of ore that extend into the underlying Knowlton massive flow interior footwall and are closely associated with strike-parallel fractures and veins. The grade of the ore in the flow top may correlate with these footwall pockets of ore; there is an approximate strike parallel (drift parallel) orientation of the grade of the ore (Fig. 1.5). The workings of the Caledonia Mine provide excellent access to observe the 3-D geometry of the Knowlton lode. An elongated volume of highly epidotized basalt characterizes a footwall ore pocket that was mined out in the 1990s by Red Metal Minerals and will be visited on this field trip.

Veins are of two types. Veins within the Knowlton flow top that extend into underlying Knowlton massive flow interior and contain the same basic minerals as those found in the lode itself (including native copper) are considered synchronous with the native copper deposit at the Caledonia Mine. Native copper occurs as small to large masses in the fractures and seems to be more abundant in the overlying adjacent tabular ore body within the lava flow top. The fractures typically have little or no displacement. Adjacent to the fractures even massive basalt can be highly altered and host native copper. One main-stage vein that has been studied in more detail by Bornhorst strikes subparallel with the strike of the flow top but dips more steeply, about 80°NW dip of the vein as compared to 45°NW of the lava flow top. This vein has been traced along strike for over 100 m. It extends into the footwall, but is hard to identify as it enters the lode. Within this vein the intensity of alteration varies from slight to very high. Original basalt can be completely converted to a green soft epidote and lesser chlorite rock, or a hard epidote and lesser quartz rock. Overall mineralogy and paragenesis in the vein is similar to the lode. The vein contains pockets of a soft blue-green mineral identified as corrensite by XRD (mixed layered clay mineral with 50/50 chlorite and smectite unit cells stacked in perfect alternation).

Figure 1.6: Cross-section sketch of the topography of Caledonia bluff showing the positions of the Caledonia Mine adit and the top of the Knowlton lava flow.
This vein has yielded outstanding museum quality specimens of crystalline native silver (now part of the A.E. Seaman Mineral Museum collection). These native silver specimens were encased in white calcite; the calcite was removed by acid cleaning. This vein also yielded clusters of colorless calcite crystals internally laced with native copper from open vugs. Several masses of native copper weighing over 100 kg and small groups of copper crystals originally encased in white calcite (removed by acid cleaning) have also been recovered during exploration. Some of the copper crystals were coated with very small cubic native silver crystals. There are multiple other veins at Caledonia synchronous with native copper precipitation. One of these veins along the drift that will be visited is notable for hosting datolite; the datolite commonly contains very-fine inclusions of native copper. The occurrence of veins at the Caledonia Mine is quite similar to veins described by Broderick (1931) occurring in the Baltic and Isle Royale Mines near Houghton. At Caledonia, they are interpreted as pathways for ascending hydrothermal fluids and thus, played an important role in the deposition of native copper and associated minerals. At Caledonia, there are veins that crosscut the native copper mineralized lode. These post-copper mineralization veins contain calcite and laumontite and are barren of copper. Several of these post-mineral veins are readily visible along the down-dip side of the Caledonia adit.

At the Caledonia Mine, the most abundant mineral filling amygdules and spaces between fragments in the Knowlton lode is calcite which is closely followed by subequal amounts of quartz, epidote and red K-feldspar. There are lesser amounts of prehnite, pumpellyite and chlorite. Native copper is present in small amounts with an average grade of about 1.2 % Cu. Native silver and datolite are present in much lesser amounts. Least abundant are laumontite, adularia, and corrensite (clay mineral). No major differences exist in the abundance of secondary minerals averaged over the scale of 100's of meters. In contrast, over the scale of a few meters the distribution of secondary minerals is variable to highly variable. While a secondary mineral may be completely absent in one zone and extremely abundant in another, the meter scale variation does display a degree of regularity. For example, within the Knowlton flow top secondary minerals may occur in overlapping bands; the bands are consistent with the progressive filling of open spaces indicated by amygdule paragenesis. The intensity of alteration is highest near both the hanging wall and footwall of the brecciated flow top lode where apparently there was preferential flow of hydrothermal fluids. Distribution of secondary minerals also has a poorly defined correlation with the occurrence of synchronous veins. In general, native copper tends to be more commonly associated with epidote, calcite, and quartz. Rarely is native copper abundant in areas with abundant K-feldspar.

Paragenetically, K-feldspar is an early formed mineral followed by epidote and then datolite, prehnite, pumpellyite, chlorite, calcite and quartz. Native copper is found as inclusions in epidote, calcite, quartz, and datolite. Much of the calcite that is overall synchronous with native copper precipitation does not contain obvious inclusions of native copper. Post-native copper mineralization hydrothermal minerals in veins and open space fillings as coatings on earlier formed minerals include calcite, laumontite, adularia, and corrensite. These likely formed from superposition of later lower temperature hydrothermal fluids on earlier higher temperature formed minerals associated with native copper during collapse of the hydrothermal system. This relationship is found elsewhere in the broader district.
Post-emplacement alteration of hydrothermal minerals is most obvious for native copper. At Caledonia, tenorite and cuprite (Cu oxide) often but not always occurs as a thin coating on native copper that is found in open space fillings. The tenorite and cuprite could have its origin during Precambrian weathering and downward-percolating ancient groundwater leading to supergene alteration of the native copper prior to Phanerozoic marine submergence or during more recently since Pleistocene glaciations eroded and exposed the Caledonia deposits at the surface. Today, only a few fractures within the stopes of Knowlton lode are damp with meteoric groundwater despite the shallow depth, an argument in favor of Precambrian tenorite and cuprite. However, the presence of modern groundwater flow into the mine, such as near the intersection of the cross-cut and the Knowlton drift, suggests Pleistocene age for the tenorite and cuprite cannot be precluded. In addition to tenorite and cuprite, there are occasional copper carbonate minerals (such as malachite), brochantite (hydrated Cu sulfate), atacamite (hydrated Cu chloride) and unknown green to blue-green minerals on native copper surfaces. These may also be supergene in origin. However, there is at least one mineral, gerhardtite (hydrated Cu nitrate) that is the result of post-mining chemical reactions.

An extension of the Caledonia adit cuts across the lava flows towards the Nebraska Mine; the cross-cut was a component of Calumet and Hecla’s exploration program (Fig. 1.5). This cross-cut intersects the South Knowlton lava flow top directly below the base of the Knowlton lava flow. An NSF-sponsored Teachers Earth Science Institute (educating middle and high school teachers about mining) drilled, blasted, and mucked out the South Knowlton lava flow top to its present expanded opening in the early 2000s. Below the South Knowlton, there are several thin basalt lava flows that can be identified before the stratigraphic level of the Butler lava flow. While the Butler lava flow top is readily identified in the cross-cut by abundant amygdules filled with K-feldspar and calcite, it lacks significant native copper here. A small fault can also be seen along the cross-cut. This cross-cut and adit connects the Caledonia Mine to the Nebraska Mine where the Butler lava flow top was a principal target of mining.

Mining History of the Caledonia Mine

The Caledonia Mining Company began its operations in 1863 after acquisition of the mining rights of the former Nebraska Company and acquisition of the adjacent Kansas Properties. The workings at that time consisted of a horizontal adit driven about 90 m to the Butler deposit on the west end of the Caledonia bluff and two shafts about 60 m deep (Nebraska Mine) (Fig. 1.5). A vein showing mineralization was explored on the north side of the bluff by four adits and while the vein proved to contain too little copper, the adits intersected the Knowlton, South Knowlton, Mass, and Butler lava flow tops. About 900,000 lbs of refined was produced from 1863 to 1870 by the mining of native copper at a grade of about 1.25 % Cu from the Knowlton and Butler lava flow tops. Production halted in 1870 when a fire destroyed the processing facility. Subsequently, the Caledonia Mining Company acquired the Flintsteel properties in 1870 and despite investing in a new processing facility, the Caledonia operations closed before significant ore was processed. Captain Martin leased the Caledonia properties and from 1873 to 1881 produced more than 330,000 lbs of copper, including a single mass weighing 80,000 lbs (40 short tons). After the lease expired, mining ceased. In 1901 there was a failed proposal to merge the Caledonia properties with other mineral rights in the Greenland-Mass subdistrict and to construct a processing facility on Lake Superior some distance away. There was no reported mining from the Caledonia properties for 56 years from 1881 to 1937.
The Calumet and Hecla Consolidated Mining Company was the major producer of copper from the mines north of Houghton. Calumet and Hecla did exploration core drilling and reopened the Caledonia adit. They drifted some 600 m along the strike of the Knowlton flow top and estimated the grade of native copper ore to be 1.45 % Cu. The workings from the nearby Nebraska Mine were connected to the Caledonia with a cross-cut and adit. Exploration of the Caledonia Mine by Calumet and Hecla ended in c.a. 1941 as a result of World War II. After World War II, Calumet and Hecla resumed exploration of Caledonia and removed a 200 ton bulk sample from the Knowlton lode in 1950. The sample had a very promising grade of 1.84 % Cu. From 1951 to 1958, Calumet and Hecla produced 5.55 million lbs of refined copper with an average grade of 1.24 %. This program included the stoping on the Knowlton lode visible above the drift today. Subsequently, Copper Range Company acquired the mineral rights at the Caledonia Mine. The Caledonia Mine was a candidate for in-situ leaching of Cu, hence a limited evaluation of the mine was completed by Copper Range and the U.S. Bureau of Mines from 1971 to 1972. The in-situ leaching option was abandoned due to potential problems with groundwater pollution.

In 1985, Red Metal Minerals acquired the mineral rights for the Caledonia Mine and other properties in the Greenland-Mass subdistrict from the Copper Range Company. The Caledonia adit was reopened and reconditioned to undertake a limited program of exploration. Red Metal Minerals mucked out broken rock as well as drilled and blasted new areas to recover native copper and other minerals. Over 28 years from 1985 to present, Red Metal has removed a single mass weighing 3000 lbs. Masses of recovered native copper are sold to the general public and mineral collectors. Red Metal distributes native copper on a wholesale basis to retail outlets that distribute Caledonia native copper around the world. You may find native copper from the Caledonia Mine for sale in unexpected places, even visitor gift shops at other copper mines! A large mass of native copper is on exhibit at the A.E. Seaman Mineral Museum, on the campus of Michigan Tech in Houghton. When the native copper is dispersed through the rock, Red Metal uses this material to prepare decorative bookends and cut slabs. The Caledonia Mine has yielded minerals sought after by mineral collectors such as native copper crystals, native silver crystals, datolite nodules, copper in calcite crystals as well as adularia and epidote. At this time, Red Metal does not undertake in underground drilling and blasting to recover specimens from the mine. Instead, the Caledonia Mine serves as an educational facility, used by Michigan Tech and others, and to recover specimens from already broken rock for resale in the general public and mineral collector markets. Since most of the native copper mines of the Keweenaw Peninsula are closed and flooded, the Caledonia Mine is significant today because it provides rare access to observe the character of native copper mineralization underground in three dimensions.

Acknowledgements

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References


FIELD TRIP 2

Geology and Hydrogeology of the Copperwood Deposit,
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Introduction

The Copperwood deposit is a stratiform copper deposit in Gogebic County, Upper Peninsula, Michigan that is hosted by gray to black shales and siltstones filling the Midcontinent rift (MCR) (Fig. 2.1). Copperwood is a reduced-facies or Kuperschiefer-type sedimentary rock-hosted stratiform copper deposit (Bornhorst and Williams (2013)). Mineralization at Copperwood contains 33.2 million short tons of Canadian National Instrument 43-101 compliant Measured and Indicated resources with an average grade of 1.65 % Cu and 4.34 ppm Ag. There are 3.0 million short tons of inferred resources with an average grade of 1.07 % Cu and 2.01 ppm Ag (Ward 2011). The resources are based on a cutoff composite grade of 0.8 % Cu and thickness of 5 ft (1.5 m).

The Porcupine Mountains sedimentary rock-hosted copper district (Bornhorst and Barron, 2011) encompasses the White Pine Mine and the Copperwood deposit (Fig. 2.1). The White Pine Mine produced approximately 4.5 billion lbs of Cu and 50 million ounces of Ag from 1953 to 1996 with a few interruptions in production. Copperwood was discovered in 1956 (a subsidiary of AMAX) after a USGS publication in Economic Geology (White and Wright, 1954) indicated potential for copper mineralization in the Western Syncline. In addition to Copperwood, the U. S. Metals and Refining Company exploration program discovered 3 lower grade mineralized areas within the Western Syncline with indicated and inferred resources of 1,348 million short tons with an average grade of 1.34 % Cu (Kulla and Thomas, 2011). During 1957 to 1958, a 71 m vertical shaft, 635 m of drifting, and 3 small stopes were completed in the higher grade Copperwood deposit (Bornhorst and Williams, 2013). A mine was not developed because of presumed ground stability issues that would force excess dilution during mining. Advances in mining technology combined with higher Cu prices make Copperwood an economic deposit today. Orvana Minerals Corp began exploration and environmental baseline studies at Copperwood in 2008. This was quickly followed by the first Canadian National Instrument 43-101 compliant mineral resource reported in 2010 (Kulla and Parker, 2010), prefeasibility in 2011, and feasibility in 2012 (Keane et al., 2012). Copperwood was granted a mining permit by the State of Michigan in 2012 and in February 2013, the Michigan Department of Environmental Quality granted the wetlands permit which is the last major permit needed before construction and production can proceed. Production is projected to begin in the near future.

The descriptions in this field guide are based on Orvana (2011) and Bornhorst and Williams (2013). This field guide is published with permission granted by Orvana Minerals Corporation; however, the content is the sole responsibility of the authors.

Regional Geologic Setting

The broad 300 km wide MCR in Michigan consists of more than 25 km thick succession of rift-filling tholeiitic flood basalts with minor interbedded red conglomerates and sandstones overlain by 8 km thick succession of rift-filling clastic sedimentary rocks (Cannon, 1993). A rift-flanking basin is filled with 3 km of sandstone. These rocks are make up the Keweenawan Supergroup in Michigan and were deposited from 1.15 to about 1.03 Ga (Fig. 2.2) (Heaman et al., 2007; Davis and Paces, 1990; Cannon et al., 1989).
The bedrock at Copperwood is part of the rift-filling clastic sedimentary rocks. Continental compression occurred at 1.06 Ga in response to the Grenvillian collision along the eastern edge of the North American continent inverting the original graben-bounding faults into reverse thrust faults (Fig. 2.2) (Cannon, 1994). A syncline at Copperwood is a result of this compressional event.

Erosion followed continental compression from about 1.03 Ga to 0.5 Ga (500 Ma) during which time multiple km of bedrock was removed and likely exposing the Copperwood orebody at the bedrock. This would have allowed a period of downward percolating groundwater into the Copperwood deposit (Bornhorst and Robinson, 2004). Marine submergence beginning 500 Ma buried the Precambrian bedrock under multiple km of Phanerozoic sedimentary rocks; evidence of Phanerozoic rocks is missing at Copperwood.

Figure 2.1: Generalized bedrock geologic map of the Midcontinent Rift. Modified from Bornhorst and Barron (2011).
Pleistocene glaciation over the last 2 million years removed the Phanerozoic rocks overlying Copperwood and once again exposed the orebody at the surface. The retreat of the last glaciers about 10,000 years ago left behind unconsolidated glacial deposits that today overlie the Precambrian bedrock at Copperwood.

Peterson (1985, 1986) determined that four distinct advances of glacial ice occurred in the western Upper Peninsula during the late Wisconsinan time (14,500 to 10,200 years B.P.). Two of these advances and retreats produced the current surficial features at Copperwood. The first advance moved out of the Lake Superior basin south to the Wisconsin-Michigan border and upon retreat, left behind the lower till. The youngest advance occurred approximately 10,200 years B.P., when the glacier overrode previous till deposits at Copperwood. The approximate southern limit of this last advance was approximately 3 km south of Copperwood. Following this final retreat, glacial Lake Duluth covered the Copperwood area. Several Lake Duluth shorelines are evident along the topography at Copperwood.

Figure 2.2: Bedrock geologic map and lithostratigraphic column for the western part of the Upper Peninsula of Michigan. The location of the field trip stops are shown.
Mesoproterozoic Bedrock Geology

The Copperwood deposit is on the southwest limb of the open shallow-plunging Western Syncline (Fig. 2.3). The bedrock at Copperwood consists of clastic sedimentary rocks of the Mesoproterozoic Oronto Group (Fig. 2.2) that strike approximately east-west and dip approximately 10 degrees to the north. The MCR bedrock at Copperwood is overlain by unconsolidated Pleistocene glacial sediments.

The lowermost lithostratigraphic layer at Copperwood is the Copper Harbor Formation that consists of primarily of reddish-sandstone. The Nonesuch Formation overlies and interfingers with the Copper Harbor Formation. It consists of gray-black shale and siltstone to gray-white siltstone to brownish-red siltstone that are subdivided into multiple informal subunits. The Freda Formation gradationally overlies the Nonesuch Formation and consists of brown siltstone at Copperwood.

Lithostratigraphy

Copper Harbor Formation. Overall, the Copper Harbor Formation is composed of red-brown conglomerates and sandstones with lesser siltstones in an upward- and basinward-fining sequence. In Michigan, there is a maximum exposed thickness of about 2,000 m (Elmore 1984). The Copper Harbor Formation sedimentary rocks are fluvial and deposited a coalescing alluvial fan environment.

At Copperwood, the Copper Harbor Formation is the oldest lithostratigraphic bedrock formation. It is lithologically dominated by red-brown to white and gray fine- to coarse-grained, arkosic sandstone. The Copper Harbor Formation in one drill hole consisted of 140 m of sandstone, a 1 m thick red, matrix-supported conglomerate, and more sandstone. Outcrops of the Copper Harbor Formation along the southern portions of Namebinag Creek and an unnamed creek indicate an increase in conglomerate facies in the lower portions of the formation. Outcrops along these streams are predominantly conglomerates with lesser amounts of sandstones.

The uppermost few feet of the Copper Harbor Formation intersects in all of the Orvana and legacy exploration drilling at Copperwood. The uppermost Copper Harbor Formation consists of interlaminated red-brown siltstones and shales with occasional beds of very fine-grained sandstones. Uncommonly, there are interbedded, thin beds of dark-gray shales and siltstones less than 1.5 cm below the upper contact indicative of interfingering overlying Nonesuch lithologies. Absent in some holes, is the red-brown siltstone at the top of the Copper Harbor Formation. It can be up to 1 m thick, but is typically less than 30 cm in thickness. Assay data has shown, the uppermost 1 m of the Copper Harbor Formation (red-brown siltstone and sandstone) does not carry significant amounts of copper. There is a dramatic and abrupt change from the reddish Copper Harbor Formation to dark-gray to black shales and siltstones of the overlying Nonesuch Formation. At Copperwood, this abrupt transition defines the change from the Copper Harbor Formation to the Nonesuch Formation.
Figure 2.3: Geologic map of the Western Syncline and Copperwood deposit. Modified from Bornhorst and Williams (2013).
**Nonesuch Formation.** Overall, the Nonesuch Formation is composed of characteristically black-to-gray-green siltstones, shales, carbonate laminates, and minor sandstones with a maximum thickness of 215 m. Elmore et al. (1989) and Suszek (1997) interpreted the depositional environment of the Nonesuch Formation to be dominantly anoxic lacustrine ranging from marginal lacustrine (sandflat-mudflat) to lacustrine to lacustrine-to-fluvial subenvironments.

At Copperwood, a completed stratigraphic section is exposed in the northeast part of the property, at a thickness of 200 to 215 m. The upper contact is missing due to erosion throughout most of Copperwood property. The formation has been subdivided into multiple informal members on the basis of lithologic variations (Fig. 2.4). All of these members have remarkable lateral continuity throughout the Copperwood area (Fig. 2.5).

The Parting Shale member is at the base of the Nonesuch Formation and is further subdivided into units (Fig. 2.4). The three lower units of the Parting Shale are the host to copper mineralization at Copperwood and together are termed the Copper-Bearing Sequence (CBS).

The lowermost unit of the Parting Shale and CBS is termed Domino after terminology used at the White Pine Mine. Domino averages 1.6 m thick in the western sector and thins to about 60 cm thick in the eastern sector. The overall average thickness is 90 cm with a range from 9 cm to 2.3 m. Domino is characterized by laminated dark-gray to black shales and siltstones. Domino hosts the highest-grade copper at Copperwood. The contact between Domino and the overlying Red Massive unit is sharp and easily recognized in drill core as an abrupt change from the dark gray/black (Domino) to red-brown (Red Massive).

The Red Massive unit of the Parting Shale and medial unit of CBS averages 35 cm thick, ranges in thickness from near zero to 1.2 m, but is usually less than 50 cm thick. It is somewhat thicker in the eastern sector than in the western sector. Red Massive is characterized by massive dark red-brown siltstones with interbedded red-brown, fine-grained sandstones. The contact between Red Massive and the overlying Gray Laminated unit is gradational and is placed where the color changes from reddish gray to gray.

The Gray Laminated unit of the Parting Shale and upper unit of CBS averages 1.1 m thick and ranges in thickness from 50 cm to 4 m. Gray Laminated is characterized by of light-to-medium, gray-to-reddish-gray laminated siltstones; some intervals are massive. The contact between Gray Laminated and the overlying Red Laminated is gradational and is placed where the color changes from gray-dominated to mixed maroon and gray.

The Red Laminated unit of the Parting Shale and hanging wall of the CBS ranges in thickness from 10 cm to 3.4 m and is more typically 1.2 to 1.8 m thick. Red Laminated is characterized by laminated siltstones with bimodal color distribution of maroon/red-brown and gray. Typical Red Laminated has mottled or wavy maroon intervals interspersed with medium-gray to reddish-gray siltstones. The contact between Red Laminated and the overlying Gray Siltstone is gradational.
Figure 2.4: Lithostratigraphic column of Copperwood bedrock units with detail of Parting Shale member. Modified from Bornhorst and Williams (2013).
Freda Formation. The top of the Nonesuch Formation gradually transitions into the Freda Formation over an interval of about 10 m where beds of coarse, light-brown siltstones and massive to cross-bedded, dark reddish-brown siltstones are intercalated with grayish-red siltstones. The contact is placed at the base of a brown to white, cross-bedded siltstone. At Copperwood, the Freda Formation is up to 120 m thick above and consists of brown siltstone. Only the base of the formation occurs at Copperwood as the rest has been removed by erosion.

Structure

The structure at Copperwood is simple and consists of bedrock units that dip gently to the north on the southwest limb of the Western Syncline (Fig. 2.5). Under the unconsolidated glacial sediments, dips for all bedrock units vary from 12° in the south near the subcrop to 8° in the north nearer the synclinal axis. The bottom surface of the CBS approximates a gently curved, dipping plane lacking significant undulations.

One fault has been identified at Copperwood (Fig. 2.3). This fault is interpreted to be a shallow, north-dipping reverse fault with 3 to 7 m of vertical displacement. Minor fractures with less than 1 inch of displacement were observed in multiple holes and these fractures are typically healed by calcite.

Figure 2.5: Geologic cross section of the Copperwood deposit. Modified from Bornhorst and Williams (2013).
**Copperwood Deposit**

At Copperwood, copper mineralization is hosted by gray to black shales and siltstones of the CBS (Fig. 2.4). The footwall consists of red-bed sandstones and minor siltstones of the Copper Harbor Formation and the hanging wall consists of maroon/red-brown to gray siltstones of the Red Laminated unit. Geologic cross sections using the base of the CBS as the horizontal datum demonstrate the high degree of lithologic continuity of the CBS. The copper orebody is a conformable and tabular with an average thickness of 2.5 m. In the western sector the CBS averages 2.9 m thick whereas in the eastern sector it averages 2.1 m thick. The Copperwood deposit contains a total (all categories) undiluted geologic resource of about 1.16 billion lbs of Cu and 4.4 million ounces of Ag.

The deposit (CBS) is characterized by copper in the form of chalcocite with minor amounts of silver. Other copper minerals such as chalcopyrite and bornite occur above the CBS (Bornhorst and Williams, 2013). Pyrite is virtually nonexistent in the CBS, but above the Parting Shale, pyrite does occur in low abundance. The CBS is dominantly siltstones that are composed of over 90% silicate minerals (quartz, clinochlore, muscovite, illite, K-feldspar, plagioclase), about 2% calcite, and 3% hematite. Overall, pyrite and other minerals with the potential to generate acids are lacking whereas calcite, which is an acid-neutralizing mineral species, is abundant.

The White Pine Mine produced copper from almost the entire Parting Shale and from the overlying Upper Shale (Fig. 2.4) (Mauk, 1992; Ensign et al., 1968). Whereas the three layers that compose the CBS at Copperwood are lithologically similar to those at the White Pine Mine, their thicknesses and proportions are not. The total Parting Shale is much thicker at Copperwood and e.g., the Domino within the western sector is typically 2.5 times thicker than at White Pine. At the White Pine Mine, the ore minerals are chalcocite and native copper whereas Copperwood is devoid of native copper. At White Pine, the chalcocite and minor native copper is stratiform ore interpreted as being related to diagenesis (Brown, 1971; Ensign et al., 1968). The native copper represents a second stage of mineralization (Mauk et al., 1992) hosted in faults and fractures and is interpreted as being related to the native copper deposits of the Keweenaw Peninsula (Bornhorst, 1997). Copperwood lacks the complexity of the White Pine deposit (Bornhorst and Williams, 2013).

The White Pine copper deposit straddles a right-lateral strike-slip fault and an anticline (Ensign et al., 1968; Johnson et al., 1995). Thrust faults, strike-slip faults, and normal faults are encountered throughout White Pine and these faults and folds are mostly related to late rift compression. Some clearly compression-related thrust faults host sheets of native copper. The second-stage mineralizing fluids were likely of the same origin as those related to native copper in the Keweenaw Peninsula (Bornhorst, 1997).

The Copperwood deposit is an example of a reduced facies or Kupferschiefer-type sedimentary rock-hosted copper deposit (Bornhorst and Williams, 2013). Bornhorst and Williams (2013) proposed that at Copperwood "chalcocite replacement of pyrite in unlithified sediments during diagenesis is a result of emanating upward-focused, compaction-driven, Cu-bearing saline basinal
waters whose Cu was leached from the underlying red-bed paleoaquifer.” In comparison to most examples of reduced facies or Kupferschiefer-type (Hitzman et al., 2010, 2005; Cox et al., 2003), Copperwood is notable for its simplicity (Bornhorst and Williams, 2013).

**Pleistocene Unconsolidated Glacial Deposits**

The unconsolidated deposits at Copperwood consist primarily of a reddish-brown glacial till. This glacial till unconformably overlies the bedrock and ranges in thickness from 0 (at outcrops along streambeds south of the subcrop of the Copperwood deposit) to 43 m; average thickness is approximately 25 m (Fig. 2.6). The top of the bedrock surface is generally smooth. Boulders or otherwise weathered bedrock were encountered in some borings at the bedrock surface, but at most locations the glacial till sits on a scoured bedrock surface. The surface of the bedrock is more or less parallel to the ground surface topography, and slopes toward the north-northwest.

![Figure 2.6: Schematic cross section through the Copperwood project with generalized geology.](image)

The glacial till at Copperwood is a mud-matrix supported diamictite. This diamictite is massive with no stratification, laminar or thinning upward or downward and the matrix is a uniform mix of sand, silt, and clay. Grain-size distribution curves are typical of those associated with subglacial tills (Fig. 2.7). The characteristics lead to the interpretation of the glacial till at Copperwood as a subglacial diamictite (Kemmis, 2008), meaning that it was deposited beneath the glacial ice. The diamictite is dense and overconsolidated, characteristic of subglacial till, but unlike normally consolidated to slightly overconsolidated lacustrine deposits.

The glacial till was described during the soil boring program as variations of a silty clay based on slight variations in the observed portions of silt, clay, and sand. Field classification ranged from silt, clay, silty clay, clayey silt, silty sand, and sandy silt. The till was found to contain trace (1 to 9%) to little (10 to 19%) to some (20 to 34%) amounts of sand and gravel. Soil samples tested for particle size distribution indicated that the average composition of the cohesive (silt/clay) was
Figure 2.7: Grain size distribution of glacial till samples from the Copperwood site.

approximately 50% silt, 20% clay, and 30% sand (Fig. 2.8). Analysis of the fine fraction of the till (<200 sieve size) by X-ray diffraction indicate that quartz was the major component, with very little clay minerals (kaolinite, illite, montmorillonite, etc.) present. Analyses also indicated the presence of small amounts of feldspar, micas, calcite, and hematite. Testing using dilute hydrochloric acid indicated the presence of very finely-ground calcite, volumetrically too low to be detected by X-ray diffraction. The gravel/cobble portion was difficult to estimate from the laboratory analyses, due to the mass of the samples subjected to sieve analysis. Some samples contained no gravel-sized fraction, while others contain up to 45% (by dry weight) of gravel (coarse and fine). Inspection of Rotosonic soil cores revealed as much as 10 to 20% coarse fraction (% gravel by volume) in the recovered soil core. Gravel, cobbles and boulders larger than 9 cm (diameter of drill sampling device) were encountered during the drilling as well as during site reconnaissance activities. Large boulders (up to 1 m in diameter) are present within the bluffs along the Lake Superior shoreline. The gravel portion of the till consisted of dark reddish-brown sandstone (between 60% and 70%), diabase (between 8% and 18%), granite/gneiss (between 7% and 13%), basalt/amygdaloid (between 1% and 5%), and other types of rocks (between 2% and 8%). The sandstone and basalt are likely to have been locally derived from the Keweenawan Supergroup bedrock. Beach stones on the Lake Superior shoreline represent a material washed from the entire thickness of the till outcrops along the lakeshore. The predominance of red sandstone (likely Freda Formation) in the till accounts for the overall red-brown color of the glacial material.
Figure 2.8: Soil texture plot of glacial deposits from the Copperwood site.

Figure 2.9: Stratigraphic section of the glacial overburden deposits at the Copperwood site.
The glacial till can be divided into two units (upper till and lower till), based on matrix grain size, amount and size of gravel, and vertical distribution (Fig. 2.9). In addition, there are thin (< 3 m with an average thickness of < 1 m) and isolated layers of coarser (non-cohesive) sediments which are located predominantly between the upper and lower till units. These generally consisted of fine to medium sand with varying amounts of silt and clay. These granular deposits, when encountered, are not laterally extensive, and for the most part cannot be correlated between adjacent borings. They are interpreted as lacustrine, intra-till sands or subglacial meltwater deposits. Additional granular deposits were found in three borings at the base of the overburden, on the top of the bedrock surface.

Peterson (1985) described the glacial deposits of the area as thin (< 10 m) drift over bedrock. Hack (1965) described the Ontonagon Plain (located on the east side of the Porcupine Mountains) to be underlain by reddish-brown glacial lake sediments and till. He described three units within the glacial deposits – the lower, intermediate, and upper units. The lower unit is described as a stony till containing locally derived subangular boulders and fragments. The intermediate unit is described as till and laminated silt and clay in distinct layers that were believed to be lacustrine sediments. This unit is less stony than the lower unit. The upper unit is described as a clayey till that is much less stony than either of the lower units. Thin lacustrine deposits related to glacial Lake Duluth are described as a patchy thin (< 60 cm) overlying veneer of strongly-laminated clay, silt and sand of variable thickness. These glacial deposits were streamlined by glacial movement into elongated drumlins and flutes.

The three primary glacial units described by Hack (1965) are present at Copperwood: the lower till which is slightly coarser grained with more (and larger) clasts than the upper till, the intermediate unit, less well defined at Copperwood, but composed of the laterally inconsistent layers of silty and sandy sediments, and the upper till. A thin (< 1 m thick) veneer of lacustrine deposits related to Lake Duluth exists at Copperwood. While the flutes or ridges are not obvious at Copperwood as they are on the Ontonagon Plain, such features may have been the cause of the distinct modern Copperwood drainage pattern.

**Groundwater**

Groundwater elevation data collected from the well network at Copperwood indicates that the groundwater in the glacial deposits, upper portions of the Copper Harbor formation, and the Nonesuch formation flow to the north-northwest, toward Lake Superior, and generally follows the slope of ground surface topography. The indicated groundwater velocity is from 0.63 to nearly 2.8 feet per year (fpy) within the bedrock units and from 0.7 fpy to nearly 1.1 fpy in the glacial deposits.

The highest concentrations of total dissolved solids (TDS) and chloride in the groundwater are located in the top of the Copper Harbor Formation and the bottom of the Nonesuch Formation; concentrations decrease upward through the Nonesuch (Fig. 2.10). The groundwater in the glacial deposits generally contains much lower TDS concentrations. There is very little connection between groundwater within the various units, except for the uppermost unit in the glacial deposits which illustrates characteristics of recharge from surface water.
Groundwater in the uppermost portions (upper 30 feet) of the glacial deposits has relatively low
TDS (average of 477 mg/L). It is depleted in sodium, chloride, and sulfate, and is mainly
calcium bicarbonate type water. This water type is typical of groundwater near a precipitation-
fed recharge zone that has had relatively short contact time with the geologic materials.

Groundwater within the remainder of glacial deposits has an average TDS of 878 mg/L (ranging
between 110 mg/L to 7,300 mg/L) and it is depleted in magnesium and sulfate. The ion
composition varies from sodium chloride, calcium chloride, sodium bicarbonate/carbonate, to
calcium bicarbonate/carbonate water types. These variations in water type and TDS
concentrations indicate the groundwater is not in connection with a precipitation-fed recharge
zone and lacks connection with or flow path between the overlying uppermost zone. Sodium-
and/or chloride-type water typically indicates that groundwater is equilibrating with the
surrounding geologic matrix.

For wells screened in the Nonesuch Formation, TDS ranges between 115 mg/L to 34,000 mg/L,
with an average of 6,800 mg/L, which is about eight times that for groundwater residing in the
overlying glacial deposits. Calcium chloride is the dominant water type, particularly when TDS
is elevated. Sodium is also a dominant cation in groundwater at some wells. This groundwater
is not near a precipitation-fed recharge zone and is not connected with the overlying glacial
deposits.

Wells screened in the Copper Harbor Conglomerate have a range of TDS between 140 mg/L to
66,000 mg/L, with an average of 10,545 mg/L, which is about 1.5 times that for groundwater in
the overlying Nonesuch Formation. Groundwater in one well has TDS at 66,000 mg/L, which is
greater than the TDS of sea water (35,000 mg/L). The groundwater is calcium-chloride type. In
addition to calcium and chloride, sodium and bicarbonate/carbonate ions are dominant in
groundwater from wells with lower TDS. This groundwater lacks connection with other
groundwater zones beneath the site.

Surface Water

The surficial drainage system at Copperwood is part of the Lake Superior watershed and is
composed entirely of small streams, roughly parallel to one another, flowing to the northwest
from higher ground towards the south directly into Lake Superior. There are no lakes at
Copperwood. Water flow within the streams is flashy and significantly controlled by timing and
duration of precipitation. No groundwater contribution has been observed in these streams.

High flow in streams occurs during spring when the snow melts and after significant rain events.
Flow increases and decreases quickly during rain events. All of the streams have periods of zero
measurable flow either due to dry conditions or freezing in the winter. During the summer
between rain events, a slight “trickle” of water can be observed flowing between cobbles in the
stream bed which enters and exits multiple isolated pools. The many isolated pools found on all
of the streams are also maintained by water flow just beneath the stream-bottom substrate. The
upper reaches of the streams at Copperwood can be classified as ephemeral (flow only during or
immediately after periods of precipitation) and the lower reaches as intermittent (flows only
during certain times of the year). Perennial streams, which have continuous flow, are not present
at the site. Ephemeral streams have no base flow and the stream beds are above the water table.
Intermittent streams have base flow for at least some periods of the year. At the Copperwood
Surface water at Copperwood has a neutral to slightly alkaline pH with most values are between 6.5 and 8.0. Lake Superior water is slightly alkaline (average and median pH of about 8). The average and median dissolved oxygen values for surface water (8.3 mg/L and 7.9 mg/L) and Lake Superior water (8.9 mg/L and 8.0 mg/L) indicate the waters are oxidized as is typical for surface water in contact with the atmosphere. The surface water is calcium-bicarbonate type, which is associated with precipitation and little or no contact with soil. The surface water contains TDS at levels of approximately 20% of that in the groundwater in the uppermost glacial till, which is consistent with very little groundwater contribution to surface water.

References


FIELD TRIP 3

Eagle Ni-Cu-PGE Mine and Humboldt Processing Plant,
Marquette County, Michigan

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Introduction

The Eagle property is located in the Upper Peninsula of Michigan, USA, in Michigamme Township, Marquette County, Upper Michigan Peninsula, USA (Figure 3.1).

Figure 3.1: Eagle mine location
The Eagle property is situated on the Yellow Dog Plains, a sandy glacial outwash, on the USGS 1:24,000 scale Bulldog Lake quadrangle sheet at geographic co-ordinates 46° 44' 54" north latitude by 87° 53' 43" west longitude, in Michigamme Township, Marquette County.

Public roads serving the mine project site include the Marquette County Triple A Road, which is a county road (CR) providing direct access to the mine site (distance 61km). Other roads include the CR 510 and CR 550. Public roads serving the Humboldt Mill project site are County road 601, which provides paved access to the mill property. Other roads leading to CR 601 include State Highway 95 and U.S. Highway 41. County roads 550, 510, and AAA will provide the primary access to the mine site.

Exploration History of the Eagle Project

The earliest historical accounts of exploration in the Baraga Basin date back to the mid-1800’s when a group of investors tried to develop slate quarries along the Slate River. Little documented exploration work took place in the Baraga basin between 1910 and 1950. During the 1950’s Jones and Laughlin conducted an exploration programme along the northern portion of the east branch of the Huron River, investigating uranium-silver-mercury mineralisation associated with a graphitic shear exposed in the river.

During the 1960’s and 1970’s, various interests conducted exploration programmes on Ford mineral lands in the Baraga Basin primarily focused on uranium and zinc. The U.S. Department of Energy provided funding to drill a number of deep holes in the Baraga Basin during the 1970’s presumably to provide stratigraphic information for the uranium exploration effort. Concurrently, the USGS began a bedrock-mapping programme of the basin, focusing primarily on exposures in rivers, which produced an open file outcrop map with little interpretation and no report.

In 1976, Michigan Technological University drilled a 31m hole on the east end of the Yellow Dog (Eagle East) outcrop. The hole bottomed in coarse-grained peridotite with only traces of sulfides. In 1979, the Michigan DNR, in conjunction with the USGS, published a report on the Yellow Dog peridotite describing the results of geochemical, petrographic and geophysical studies of the peridotite (Klasner, et. al., 1979). The authors concluded that the anomalous sulphur and copper contents of the outcropping peridotite indicated a significant potential for copper-nickel ore deposits.

Kennecott Exploration actively explored for Sedex zinc deposits in the region from 1991 through 1994. Field work resulted in the discovery of glacial boulders of peridotite with sulfides that indicated the potential for magmatic sulfide mineralisation. Kennecott partially shifted to magmatic nickel exploration in 1995 and drilled four holes to test the Yellow Dog peridotite (Eagle East). One hole (YD95-2) intersected 10m of moderate to heavy disseminated sulfide mineralisation along the southern contact. Two more angle holes (YD95-3 and YD95-4) collared on the east end of the Eagle East outcrop demonstrated the peridotite widened to the east but only intersected a meter or two of weak sulfide mineralisation along the north and south contacts.
Drilling at the Eagle East target in July 2001 intersected 30m of disseminated and massive sulfides averaging 1.03% Ni and 0.75% Cu (YD01-01). One of three holes at Eagle intersected 85m of disseminated sulfides averaging 0.6% Ni and 0.5% Cu (YD01-06).

In 2002 drilling at Eagle targeted the centre of a magnetic anomaly. The first hole, YD02-02, intersected 84.2m of massive pyrrhotite-pentlandite-chalcopyrite averaging 6.3% Ni and 4.0% Cu, firmly establishing the presence of economic grade and width mineralisation at Eagle. Subsequent definition drilling continues to the present day.

On October 4, 2012, the company’s legal name was changed from Kennecott Eagle Minerals Company (KEMC) to Rio Tinto Eagle Mine, LLC (RTEM). This was a change in the company name only and not a change in ownership or operational control. On July 17, 2013 Lundin Mining Corporation of Toronto, Canada purchased 100% of the Eagle assets from RTEM. The new Lundin subsidiary is called Eagle Mine, LLC.

Geology

A detailed description of the geology and mineralization of Eagle that formed the basis for many subsequent reports is found in Rossell and Coombs, 2005. A comprehensive review of the 2013 resource and reserve estimates and mining plan can be found in Owen and Meyer, 2013 (downloadable at www.sedar.com). Ding (2010, and Ding et al., 2010) give a detailed analysis of mineralogy, petrology, and isotope studies of the Eagle intrusion.

FIELD STOPS

A) Eagle Mine

The tour of the Eagle mine site will begin with a mandatory security gate site induction. The group will then proceed to the mine administration building where it will be divided into four groups. The tour will require steel toed boots, hardhats, safety glasses, safety vests, and self-contained self-rescuer (SCSR). Participants will be driven underground into the Eagle Mine and rotated in and out. Due to time and exposure constraints the tour will consist of one stop in the 215 level.

The portal to the Eagle mine is an eastward drive into the Eagle East peridotite (Figure 3.2). The original design was for a conventional opening into the outcropping of peridotite above ground. Negotiations with the State of Michigan and the Keeweenaw Bay Indian Community resulted in a design change to avoid development in the visible outcrop. The portal was shifted west to enter the peridotite below ground level.

The decline then turns north, where it crosses the contact with the surrounding graywackes and slates of the Upper Fossum Creek unit of Paleoproterozoic Baraga Group. The contact is not visible due to shotcrete coverage. From this point development is nearly completely within Upper Fossum Creek Unit.
The decline heads westerly for approximately 1.2 kilometers until it reaches access drifts and the spiral decline (Figures 3.3, 3.4, 3.5). Signs along the decline indicate levels by their actual elevation above sea level e.g. 265L.
Figure 3.4: 3D Oblique view to the southeast of decline between Eagle East and Eagle

Figure 3.5: Eagle decline and development looking south (25 meter grid).
215 Level Geology and Structure

The majority of the development from Eagle East to the 240 level encountered gently folded Baraga Basin sediments with dips within 30 degrees of horizontal. At the 240 level, a tight fold was mapped showing NW-SE striking beds turning from horizontal to vertical within 5 meters. This folding can be mapped in detail one level down, at the 215 level (Figure 3.6), and is facilitated by tracing syngenetic bedding plane pyrite beds. Detailed mapping of the 215 level shows a 25 meter zone of tight folding, often with bedding changing from 10 degrees to 90 degrees within meters (Figure 3.7). This folded zone is oriented approximately 310, and strikes roughly 30 degrees from the Eagle dike trend. Figure 3.8 is a 3D conceptual model of the bedding in the 240-215 levels superimposed on semi-massive and massive sulfide models.

Figure 3.6: 215 Level Plan Detailed Geology

Figure 3.7: 215 level (215-1545 stope access rib) looking east. Bedding at left is flat and folds upwards to 45-50 degrees over 4 meters (wire mesh is 4 inch square).
Mineralization

A massive sulfide (MSU) sill can be seen clearly following folded bedding in the 215 level. The upper contact of the MSU is a folded bedding plane where flexural slip has occurred, forming a zone of weakness that was exploited by the MSU (Figure 3.9). The other contact of the MSU is thermally eroding the sediments, and 1cm ribbons of MSU can be seen exploiting weak bedding planes (Figure 3.10). The MSU sill continues toward the north where bedding is horizontal or dipping northward. MSU mineralization appears to be structurally truncated by the vertical bedding zone.
Figure 3.9: Massive sulfide-sediment contact following bedding (215-1525 stope access face, looking south)

Figure 3.10: Massive sulfide-sediment contact (215-1525 stope access face, looking south)
Thermal Metamorphism and Alteration

Within 2 to 5 meters of the MSU, a hornfels zone can be seen. The hornfels varies from partially melted and potassically altered sediments characterized by a pink discoloration with ribbons of recrystallized K-feldspar partial melt, to lower grade thermally altered siltstone where bedding has been destroyed by recrystallization (Figure 3.11). The presence of chalcopyrite along microdefects and cleavage planes in the hornfels indicates that MSU is within about 2m.

Figure 3.11: Partially melted and potassically altered sediments (pink discoloration): wire mesh is 4 inches square (215-1525 stope access east rib).

B) Humboldt Mill

The visit to the Humboldt Mill will consist of a walking tour of construction progress and observing various drill core from the Eagle deposit. Upon arrival, all visitors will be required to attend a short building safety induction. The tour will require steel toed boots, hardhats, safety glasses, and safety vests.

Lundin is refurbishing and reusing the Humboldt Mill, a prominent fixture of Michigan’s mining history since the 1950’s. The mill was built and first used by the Cliffs Natural Resources (f.k.a. Cleveland Cliffs Iron Company) for milling of iron ore from their adjacent open pit mine. Cliffs ceased operations at the Humboldt site in the early 1980’s and sold the property to the
Callahan Mining Company. Callahan began milling gold from the Ropes Gold Mine in 1985. During this time Callahan used the pit, which naturally filled with water after Cliffs’ operations, for subaqueous disposal of its tailings. Callahan’s operation ran until 1989. The last company to use the site before Eagle was the Mineral Processing Corporation. Since 1999, the Humboldt Mill sat idle, falling into disrepair. Even so, this existing Brownfield industrial site has proven to be an important community asset.

The mill was purchased by Rio Tinto in 2008. Eagle obtained the permits necessary to refurbish and operate the mill in 2010. Between 2009 and 2011 clean-up and environmental reclamation activities of historical mining waste was performed. Construction and equipment upgrades to the mill began in 2012 to prepare the facility for ore production in 2014. The lower frontpiece photo is an aerial view of the Humbolt operations as of late summer 2013.

The mill will be utilized for the concentration of ore and disposal of tailing. Ore will be hauled from the Eagle Mine to the mill, where it will be processed into separate nickel and copper concentrates. The concentrates will then be transported via rail to an offsite smelter for further refinement.

References

Ding, Xin, 2010: Mineralogic, petrological and isotopic studies of the Eagle Ni-Cu sulfide deposit, Michigan , Ph.D., Indiana University, 156 pages


FIELD TRIP 4

Geology and Mineralization of the Tamarack Deposit, Aitkin and Carlton Counties, Minnesota

Dean Rossell and Steve Hovis
Rio Tinto – Kennecott Exploration, Salt Lake City, UT 84116
Fact sheet

Nickel-Copper exploration target at Tamarack (Minnesota, USA)

Assays from twenty-two mineralised drill holes have identified a +750 metres long body of nickel-copper sulphide mineralisation open up-plunge, down-plunge and to depth. Preliminary metallurgical test work shows excellent recoveries for both nickel and copper.

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<th>Grade Range</th>
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<td>9-11</td>
<td>1.0 – 1.1% Ni and 0.6 – 0.7% Cu</td>
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Location and Title

The Tamarack project, 75 kilometres west of Duluth, is 100 per cent owned by Rio Tinto. There is excellent established infrastructure including a paved highway adjacent to the deposit and power and rail lines within three kilometres.

Summary of Exploration Results

The Tamarack deposit was located by geophysics and reconnaissance drilling within the northern portion of a plus 15 kilometre long Proterozoic mafic-ultramafic intrusion concealed beneath 20-30 metres of glacial cover. Most of the larger intrusive system remains untested. Tamarack mineralisation comprises disseminated, semi-massive and massive sulphides within a late gabbroic phase. Massive sulphide lenses occur in country rock metasediments peripheral to the intrusion.
**Table of significant intercepts**

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<th>Interval (m)</th>
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*Reported intervals are continuous mineralized drill intercepts where composite Ni% multiplied by composite meters is greater than 50. Composite boundaries are determined using a 0.4% Ni cut-off. Intervals contain a maximum of 10% internal dilution of <0.4% Ni material.*

The exploration target being reported under clause 18 of the JORC Code is based on assessments of prospects within Rio Tinto’s 100 per cent owned tenure which are supported by drilling, geophysics, metallurgical test-work and modelling undertaken over the last year. However, the potential quantity and grade is conceptual in nature, there has been insufficient exploration to define a Mineral Resource and it is uncertain if further exploration will result in definition of a Mineral Resource.

**CP Statement**

The information in this presentation that relates to Exploration Results is based on information compiled by Steven Coombes who is a Member of the Association of Professional Engineers and Geoscientists of British Columbia, a JORC Recognised Overseas Professional Organisation (ROPO). Steven Coombes is a full time consultant for Rio Tinto and has sufficient experience which is relevant to the style of mineralisation and type of deposit under consideration and to the activity which he is undertaking to qualify as a Competent Person as defined in the 2004 Edition of the ‘Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves’. Steven Coombes consents to the matters based on his information in the form and context in which it appears.
FIELD TRIP 5

Cu-Ni-PGE Deposits of the Duluth Complex-
Geology and Development

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Kevin Boerst
Twin Metals Minnesota, Ely, Minnesota 55731

Publicly reported data from
SEC filings, 43-101 reports,
and related audits
(proven, probable, measured, indicated, inferred)

World Class Cu-Ni-PGE Ore Deposits and Camps
EXPLORATION AND DEVELOPMENT BACKGROUND
By the late Richard Patelke (PolyMet Mining) with modifications by Mark Severson

Large resources of low-grade copper-nickel sulfide ore that locally contain PGE concentrations are well documented by drilling in the basal zones of the Partridge River, Bath tub, and South Kawishiwi intrusions. At least eleven occurrences of significant mineralization have been delineated in the basal 300 to 1000 feet of these intrusions. Of these eleven occurrences, two projects are currently undergoing deposit definition drilling, including the Mesaba deposit (Teck American) and Maturi deposit (Twin Metals). Definition drilling at the Birch lake deposit (Twin Metals) took place up to 1.5 years ago. A fourth project, the NorthMet deposit (PolyMet Mining) is currently undergoing environmental review and mine permitting. Recent exploration drilling has taken place at the Nickel Lake Macrodike (Duluth Metals) and at the Serpentine deposit (Encampment Resources). Overall, the copper-nickel mineralization consists predominantly of disseminated sulfides that collectively constitute over 4.4 billion tons of material averaging 0.66% Cu and 0.20% Ni at a 0.5% Cu cut-off, according to an earlier study by Listerud and Meineke (1977).

As outlined in Miller et al. (2002a), serious exploration for Cu-Ni deposits at the base of the Duluth Complex began in 1948, about 8 miles to the southeast of Ely, MN, when strongly mineralized rocks were uncovered in an excavation used to source road material for Spruce Road. Local prospector Fred S. Childers of Ely noted copper stains in the material and he, along with Roger V. Whiteside of Duluth, began searching along the basal contact in the vicinity of the Kawishiwi River. In 1951, they diamond drilled a 188 foot deep hole and intersected mineralized gabbro that averaged 0.36% Cu and 0.13% Ni. In 1952, both Bear Creek Mining Company (BMC) and the International Nickel Company (INCO) began intensive exploration efforts along a 38 mile-long zone that coincided with the basal contact. INCO eventually picked up the Childers-Whiteside properties (Spruce Road and Maturi deposits); whereas, BMC concentrated most of their effort near the town of Babbitt which resulted in the discoveries of the Babbitt (formerly called Minnamax and now known as Mesaba) and Serpentine deposits. By 1960, these exploration efforts indicated that very large tonnages of disseminated Cu-Ni mineralization were present; however, the low-grade nature of the deposits and the unavailability of state-owned mineral lands at the time led to suspension of activities.

In 1966, state mineral leases were offered by the Minnesota Department of Natural Resources (DNR) and were awarded to successful bidders, resulting in renewed exploration activity (including the return of BMC and INCO). Since 1966, over 20 companies have been actively involved in exploration for Cu-Ni and Fe-Ti-V deposits along the basal contact of the Complex. Over 2,600 holes, totaling over 4.5 million feet of core, have been drilled. Exploration efforts during this period also defined several more deposits including: Dunka Road (now NorthMet) and Wyman Creek (United States Steel Corp.), Birch Lake (Duval Corporation and Newmont Mining), South Filson Creek (Hanna Mining), Dunka Pit (Erie Mining, BMC, and Exxon), and Wetlegs (BMC and Exxon). AMAX Exploration Inc. leased the Babbitt deposit from BMC and renamed it the Minnamax deposit in 1973. During mid to late 1970s, the Spruce Road and Minnamax deposits came closest to development. Mining plans were submitted, test shafts were sunk (one each at the Maturi and Minnamax/Mesaba deposits), surface bulk samples were collected from three sites, and various land-use and water-use permits were requested from State and Federal agencies. In 1974, the Minnesota Environmental Quality Board required that a regional Environmental Impact Statement (EIS) be conducted prior to acceptance of any site-specific EIS mining-related proposals. The DNR discontinued lease sales of State lands (1974-1982) until completion of the regional EIS. However, by the time the regional EIS was submitted in 1979, development of the Cu-Ni deposits was put on hold by the most of the mining companies involved due to weakened copper and nickel markets and the inability to make marketable (i.e., "smeltable") separate copper and nickel concentrates. Amax abandoned their plans to develop an underground high grade ore zone within the Minnamax/Mesaba deposit (known as the Local Boy ore body) in late 1982.
Then starts the “PGE” era. During the early period of drilling (prior to 1980), all of the exploration companies recognized that the Cu-Ni deposits had some potential for hosting PGEs. Based on very limited sampling, the companies assumed that the typical Cu-Ni ore contained no more than a few hundred parts per billion (ppb) combined platinum and palladium. In 1985, the DNR and Minerals Resource Research Center (MRRRC of the U of M) conducted a geochemical evaluation of portions of a Duval drill hole (DU-15), from the Birch Lake area, and found significant values of up to 9 parts per million (ppm) combined Pt and Pd (Sabelin and Iwasaki, 1985, 1986). This was at a time when demand for these elements was increasing due to their use in automotive catalysts. A short time later, Morton and Hauck (1987) compiled all of the known PGE data for the Complex and reported the presence of anomalous PGE values, often associated with high Cu values, at several other Cu-Ni deposits. These discoveries sparked renewed interest in the Cu-Ni deposits as potential polymetallic deposits (Miller et al., 2002; and references therein). E.K. Lehman and Associates of Minnesota obtained mineral leases from the state of Minnesota and began drilling wedges off the discovery hole (DU-15W) in the Birch Lake area. These Lehmann leases were later incorporated into Franconia Minerals holdings. Additional drill holes were sampled and analyzed for PGEs by several other companies throughout the Duluth Complex, and as a result, significant PGEs were found at many deposits. The occurrences of PGE mineralization for each deposit will be more thoroughly discussed later in this guidebook.

Enter the “Hydromet” era. Early development of the deposits was hampered both by state leasing issues, complex metallurgy that resulted in an inability at the time to make marketable separate Cu and Ni concentrates, and by general environmental concerns regarding sulfide mining and conventional pyrometallurgical processes. In the mid to late 1990s, the potential of developing the Cu-Ni deposits using hydrometallurgical techniques once again sparked renewed activity in the Duluth Complex. PolyMet plans to use the PlatSol technique, developed and patented by SGS Lakefield on NorthMet ores, to recover Cu, Ni, Co, and PGE at the NorthMet deposit (Dunka Road). Teck American is conducting tests on Mesaba ore to utilize its patented Cominco Engineering Services Laboratory (CESL) process to recover metals. Both Duluth Metals and Franconia have PlatSol licenses. The PlatSol and CESL processes are of similar concept, both utilizing an autoclave (pressure oxidation) process wherein sulfides are converted to sulfates and metals put into, and then recovered from, solution. Thus the sulfur air emissions of conventional smelting are eliminated and an inert and potentially marketable by-product of gypsum (calcium sulfate) is produced. Other residues from the processes are easily isolated for landfill disposal or other containment.

REGIONAL GEOLOGIC SETTING, DULUTH COMPLEX

The Duluth Complex and associated intrusions of Keweenawan age (~1.1 billion years) in northeastern Minnesota constitute one of the largest mafic intrusive complexes in the world, second only to the Bushveld Complex of South Africa (Miller et al., 2002). These rocks cover a 2,200 square mile (5,700 square km) arcuate area associated with the two strongest gravity anomalies (+50 and +70 milligals) in North America, that imply intrusive roots more than 8 miles (13 km) deep (Allen and others, 1997). The comagmatic flood basalts and intrusive rocks underlying much of northeastern Minnesota were emplaced during development of the Mesoproterozoic Midcontinent rift, which can be traced geophysically from exposures in the Lake Superior region along a 1250 mile (2,000 km) long, segmented, arcuate path to Kansas and Lower Michigan. The Duluth Complex is defined as the more or less continuous mass of mafic to felsic plutonic rocks that extends for >170 miles (275 km) in an arcuate fashion from Duluth nearly to Grand Portage (Fig. 1-1). It is bounded by a footwall of Paleoproterozoic sedimentary rocks and Archean granite-greenstone terranes (Peterson and Severson, 2002), and a hanging wall largely of comagmatic, rift related flood basalts and hypabyssal intrusions of the Beaver Bay Complex (Fig. 5-1). In genetic terms, the Duluth Complex is composed of multiple discrete intrusions of mafic to felsic
tholeiitic magmas that were episodically emplaced into the base of a volcanic edifice between 1108 and 1098 Ma.

The geology of the Duluth Complex and adjacent areas has recently been described in two major publications by the Minnesota Geological Survey (MGS). These include a 1:200,000 scale regional bedrock geological map of northeastern Minnesota (Miller et al., 2001), and a comprehensive written description of the geology depicted on this map (Miller et al., 2002), commonly referred to as the “bible” by geologists working on Duluth Complex geology. Readers’ interested in more detailed descriptions of the geologic setting of the Duluth Complex should begin their quest for knowledge by downloading these publications from the MGS website (ftp://mgssun6.mngs.umn.edu/pub2/).

Within the nearly continuous mass of intrusive igneous rock forming the Duluth Complex, four general rock series are distinguished on the basis of age, dominant lithology, internal structure, and structural position within the complex.

Felsic series—Massive granophyric granite and smaller amounts of intermediate rock that occur as a semi-continuous mass of intrusions strung along the eastern and central roof zone of the complex, that were emplaced during an early stage magmatism (~1108 Ma).

Early gabbro series—Layered sequences of dominantly gabbroic cumulates that occur along the northeastern contact of the Duluth Complex, emplaced during early stage magmatism (~1108 Ma).

Anorthositic series—Structurally complex suite of foliated, but rarely layered, plagioclase-rich gabbroic cumulates emplaced throughout the complex during main stage magmatism (~1099 Ma).

Layered series—Suite of stratiform troctolitic intrusions that comprises at least 11 variably differentiated mafic layered intrusions that occur mostly along the base of the Duluth Complex. These intrusions were emplaced shortly after the Anorthositic series (~1099 Ma).

Figure 5-1. Generalized geologic map of northeastern Minnesota (modified from Miller et al., 2002).
Rock Type and Unit Classification

Igneous rock types in the Duluth Complex are classified at each of the deposits by visually estimating the modal percentages of plagioclase, olivine, and pyroxene, and using a rock classification scheme (Figure 1-2) modified from Phinney (1972). Using this classification, the majority of rocks at the various deposits consist of troctolite, augite troctolite, anorthositic troctolite, and norite (near the basal contact) with local ultramafic layers consisting of melatroctolite to dunite. Due to subtle changes in the percentages of the estimated minerals, there can be subsequent variations in the defined rock types within a specific igneous stratigraphic rock unit on a hole by hole basis, on an interval by interval basis, and even on a geologist by geologist basis.

Figure 5-2. Modified Phinney (1972) diagram for rock type classification.

Overall, stratigraphic unit definitions are based on: dominant rock type; textural relationships; mineralogy; sulfide content; and context with respect to bounding surfaces (i.e., ultramafic horizons, oxide-rich horizons). Unit definitions are not always immediately clear in logging, but are usually clarified when drill holes are plotted on cross-sections. In other words, to correctly identify a particular stratigraphic unit, the context of the units directly above and below should also be considered.

LOCAL GEOLOGIC SETTING - PARTRIDGE RIVER, SOUTH KAWISHIWI, AND BATHTUB INTRUSIONS

By: Mark Severson

The three deposits under review for this trip are located in three of the oldest intrusions in the Duluth Complex. The NorthMet deposit and parts of the Mesaba deposit are in the Partridge River intrusion, the majority of the Mesaba deposit in the newly defined Bathtub intrusion, and Maturi deposit in the South Kawishiwi intrusion (Fig. 5-3).
Figure 5-3. Location of Cu-Ni±PGE sulfide deposits, Fe-Ti±V oxide deposits (Oxide-bearing Ultramafic Intrusion - OUI), and other exploration areas along the western edge/base of the Duluth Complex. Note that the NorthMet deposit was referred to as the Dunka Road deposit and the Mesaba deposit was referred to as the Babbitt deposit; the most recent names for these two deposits are used in this guidebook. The Birch Lake deposit will not be discussed in this guidebook.
Partridge River intrusion
The Partridge River intrusion (PRI) consists mainly of troctolitic cumulates, dips gently to the southeast, and is exposed in an arc-shaped area that extends from the Water Hen deposit, on the southwest, to the southern edge of the Mesaba/Babbitt deposit, on the northeast (Fig. 5-3). Footwall rocks include the Paleoproterozoic Virginia Formation and locally the Biwabik Iron Formation. The basal 3000 ft. (900 meters) are known in great detail from studies of abundant drill core (Severson and Hauck, 1990) and are subdivided into seven or more units that can be traced over a strike-length of 15 miles (24 kilometers).

The units of the Partridge River intrusion (PRI) are recently described in Miller and Severson (2002) and are depicted in Figure 5-4. At the base of the PRI is Unit I which consists of a suite of heterogeneous-textured troctolitic rocks that contain the vast majority of disseminated sulfide-mineralized zones. The top of Unit I is marked by a fairly persistent ultramafic horizon, which in actuality is at the base of Unit II. Within Unit I are several laterally-discontinuous ultramafic horizons and abundant footwall sedimentary inclusions of the Virginia Formation. Noritic rocks are common at the basal contact and adjacent to the inclusions due to silica contamination from assimilated footwall rocks. Unit II consists of more homogenous-textured troctolitic rocks with minor sulfide-bearing zones. However, at the Wetlegs deposit, both Units I and II contain abundant laterally-discontinuous ultramafic horizons, interbedded with troctolitic rocks that are collectively referred to as the Wetlegs Layered Interval (Fig. 5-4).

Unit III is a major marker bed throughout much of the PRI (Wetlegs to Mesaba deposits - Figs. 5-3 and 5-4) in that it is characterized by a poikilitic leucotroctolite with olivine oikocrysts that are randomly dispersed throughout the rock giving it a mottled appearance. This mottled-appearance, and the relatively fine-grained nature of Unit III, give it a distinct appearance in drill core and it is easily identified. Unit III pinches out to the west of the Wetlegs deposit and is present on only the southern fringe of the Mesaba deposit. The rapid pinch-out of Unit III to the north within the Mesaba deposit appears to be related to emplacement of a distinctly different sub-intrusion herein referred to as the Bathtub intrusion (see discussion below).

Figure 5-4. Generalized stratigraphy of the basal zone of the Partridge River intrusion (modified from Severson, 1994). Roman numerals (I through VIII) denote igneous units in the Partridge River intrusion; BT1 and BT4 denote igneous units in the Bathtub intrusion; and OUI denotes Oxide-bearing Ultramafic Intrusions.
Overlying Unit III in the PRI are units IV through VIII. Unit IV varies from a troctolite to augite troctolite, often contains an ultramafic base, and commonly grades upward into Unit V which is coarser-grained and varies from a troctolite to troctolitic anorthosite. Units VI and VII, and additional units above VII, are generally homogenous-textured troctolitic to anorthositic troctolitic rocks; each with a persistent ultramafic base that record magma injection events.

**Bathtub intrusion**

The Bathtub intrusion (BTI) is wholly contained in the central portion of the Mesaba (Babbitt) deposit. It has recently been singled out as a separate intrusion to explain the abrupt change from typical Partridge River intrusion stratigraphy in the southern part of the deposit to a completely different stratigraphy, to the north, in the remainder of the deposit (Severson and Hauck, 2008). There are three structural features that are pertinent to understanding the intrusive history of the BTI that include (Fig. 5-5): 1. an east-west trending paired syncline and anticline in the footwall rocks referred to as the Bathtub Syncline and Local Boy Anticline; 2. a zone that is closely associated with the Local Boy Anticline, referred to as the “Hidden Rise,” that separates the PRI and BTI; and 3. a north-trending fault zone, referred to as the Grano Fault, that is situated on the extreme eastern portion of the Mesaba deposit – the fault has been postulated to have been the feeder zone for the BTI and footwall-injected massive sulfides of the Local Boy ore zone.

The “Hidden Rise” is a loosely-defined zone wherein scattered hornfels inclusions, and associated noritic rocks, are fairly common. When viewed collectively, the inclusions in “The Hidden Rise” define an east-west trending “ridge” that is coincident with the Local Boy Anticline and roughly positioned at the contact between the PRI and BTI. Thus, “the “Hidden Rise” is used to both define this hornfels-bearing “ridge” and to artistically, and conveniently, divide the BTI from the PRI. The morphology of this feature suggests that it may have originally served as the floor and/or north edge of an earlier intruded PRI and later served as a wall along the south edge of the BTI as it was emplaced. The BTI has been subdivided into two main units, BT1 and BT4, each of which contain several internal subunits (Fig. 5-5). In the vicinity of the Bathtub Syncline, ultramafic layers and modally-bedded rocks are extremely common within the BT4 Unit and have been collectively referred to as the Bathtub Layered Interval (BTLI).

![Figure 5-5. Schematic “type-section” looking east through the Mesaba deposit that crudely displays the spatial distribution of most of the igneous units in the Bathtub intrusion and pertinent structural features. Note that not all of the PRI units are shown on the right side of the figure.](image-url)
Cu-rich massive sulfides are locally present at the Mesaba deposit in a small zone referred to as the Local Boy ore zone. Local Boy is positioned along the crest of the Local Boy Anticline, in close to proximity to the “Hidden Rise,” and just west of the Grano Fault. Most of the massive sulfides are associated with either hornfelsed sedimentary inclusions above the basal contact or with footwall rocks below the contact while the interfinger ing intrusive rocks are relatively barren of massive sulfides (Severson and Barnes, 1991). This suggests that the massive sulfide ores were not formed by the gravitational settling of sulfides, but rather, the ores formed by injection of an immiscible sulfide melt into structurally prepared areas within the footwall rocks along the Local Boy anticline in a vein-like setting. A possible feeder vent for the sulfide injection event may have been the Grano Fault, which was repeatedly reactivated during emplacement of the Complex. West-directed increases in Cu and PGE, associated with the massive sulfides at Local Boy, suggest that the immiscible sulfide melt fractionally crystallized and became progressively enriched in Cu and PGE as it was deposited in an east-to-west direction.

Partridge River and Bathtub intrusion footwall rocks
Because the footwall at NorthMet and Mesaba is so similar, the following is a generic description appropriate to both deposits. The drilled footwall rock types at Mesaba and NorthMet consist mainly of the Virginia Formation and Biwabik Iron Formation. Both are Paleoproterozoic in age (approximately 1.9-1.8 Ga) and are the two upper units of the Animikie Group. Any discussion on these two formations must include a description of their type-section on the Mesabi Range, as well as, a description of them as related to the metamorphism and partial melting that was produced during emplacement of the Complex. Lying beneath the Biwabik Iron Formation, but encountered in only a few drill holes are the Paleoproterozoic Pokegama quartzite (also of the Animikie Group), along with granitic rocks of the Archean Giant’s Range Batholith.

Biwabik Iron Formation
The Biwabik Iron Formation (BIF) exposed on the nearby Mesabi Range has typically been subdivided into four informal lithostratigraphic members (Wolff, 1917) that are, from the bottom up: Lower Cherty, Lower Slaty, Upper Cherty, and Upper Slaty. Diamond drill holes at Mesaba and NorthMet generally pierce the top submembers of the Upper Slaty, and end in submember C or D. Submember A is comprised of chert and marble, submember B is characterized by alternating bands of green diopside and chert with very coarse-grained hedenbergite, and submember C is a thin-bedded, green rock consisting of chert-fayalite-ferrohypersthene with black magnetite-rich bands.

Virginia Formation below the PRI and BTI
The Virginia Formation is a thick sequence of argillite, siltstone, and graywacke at the top of the Animikie Group. In close proximity to the Complex the effects of partial melting are profound and portions of the hornfelsed Virginia Formation no longer even remotely resemble a sedimentary rock. Severson et al. (1994a) subdivided the hornfelsed Virginia Formation, in both the footwall and inclusions within the Duluth Complex, into at least five informal units based largely on metamorphic attributes, which are each related to varying degrees of partial melting. These members, and a pre-Duluth Complex sill, are described below and are schematically portrayed in Figure 5-6 - although in real occurrence, this idealized metamorphic progression is more erratic, often with rapid lateral and vertical changes between the four metamorphic units discussed below.
Cordieritic hornfels
Directly beneath the basal contact of the Duluth Complex, the adjacent Virginia Formation typically consists of massive/nonfoliated, cordierite-rich hornfels that display a bluish-gray color in drill core. The rock is generally fine-grained, granoblastic, and biotite-poor (due to loss of water into the Complex) and locally may contain porphyroblastic and/or poikiloblastic cordierite. Original bedding planes are preserved in some localities, but mostly the bedding planes have been obliterated by contact metamorphism.

Recrystallized unit (RXTAL)
Beneath the cordieritic “capping” the next metamorphic variant of the Virginia Formation nearest to the Duluth Complex is a rock that is referred to as the RXTAL unit. The RXTAL unit is properly classed as a diatexite and is characterized by fine- to medium-grained cordierite, plagioclase, biotite, quartz, and K-spar with lesser amounts of Opx and opaques. Bedding planes of the original argillaceous rocks are obliterated and what remains is a massive recrystallized rock with decussate biotite that contains enclaves (blocks and folded boudins) of more structurally competent calc-silicate hornfels and thin-bedded siltstone.

Disrupted unit (DISRUPT)
With increased distance from the Complex, the RXTAL unit progressively grades into the DISRUPT unit which is a thin-bedded rock that is visibly deformed and underwent less degrees of partial melting. Textures that characterize the DISRUPT unit are bedding planes that are extremely chaotic and random in orientation due to pervasive small-scale folding, faulting, and brecciation. Superimposed on this chaotic pattern are abundant zones of leucocratic partial melts that are also chaotic and folded. The rock consists of varying amounts of quartz, cordierite, K-spar, biotite, plagioclase, and muscovite with leucosome veins and patches containing quartz, K-spar (microperthite), plagioclase, and muscovite (Duchesne, 2004). The DISRUPT unit is properly classed as a metatexite.
Graphitic argillite and Bedded Pyrrhotite (BDD PO) units

Carbonaceous argillite of the lower portion of the Virginia Formation is commonly preserved as either the BDD PO unit, or graphitic argillite, in close proximity to the Duluth Complex. This rock commonly contains over 5% disseminated pyrrhotite and/or extremely thin-bedded pyrrhotite laminae (hairline-thick), and variable amounts of graphite, staurolite(?) and sillimanite. Wherever the unit contains conspicuous and regularly-spaced laminae of pyrrhotite (0.5-3.0 mm thick at 1-20 mm spacings) it is informally referred to as the bedded pyrrhotite unit (BDD PO unit). In some areas, the BDD PO served as a local sulfur source to both disseminated and massive sulfide occurrences at the base of the Duluth Complex.

VirgSill

The VirgSill is generally present in the bottom 0.5-130 feet of the Virginia Formation, and as local apophyses into the top of the Biwabik Iron Formation. The VirgSill was intruded along the contact between the Virginia Formation and Biwabik Iron Formation and exhibits a granoblastic texture indicating that it was metamorphosed by the Duluth Complex (and thus the VirgSill is pre-Duluth Complex in age). On this basis, the VirgSill is inferred to be equivalent to the Logan sills (circa 1,109 Ma); as is another sill, the BIFSill, in the C submember of the Biwabik Iron Formation (Hauck et al., 1997). However, the VirgSill and BIFSill are different chemical entities (the VirgSill is much more Cr-enriched), and thus, these two sills may be related to at least two different intrusive events. Identification of the VirgSill in drill core is hampered by the fine-grained granoblastic texture that makes it difficult to distinguish from the enclosing hornfelsed Virginia Formation rocks; both were metamorphosed by the Duluth Complex. The VirgSill is subdivided into two textural varieties (Severson et al., 1994a; Park et al., 1999) referred to as: 1. the Massive Gray unit (MG unit) that is often logged as the Virginia Formation; and 2. a coarser-grained interior with obvious hornblende and/or olivine that is easily identified as an intrusive rock in drill core.

South Kawishiwi intrusion

The South Kawishiwi intrusion (SKI) consists mainly of troctolitic cumulates and dips gently to the southeast. The SKI is exposed in an arc-shaped area that extends from the Serpentine deposit, on the southwest, to the Spruce Road deposit, on the northeast (Fig. 5-3). Footwall rocks include the Paleoproterozoic Virginia Formation, Biwabik Iron Formation and Archean Giants Range Batholith, the latter is the dominant footwall rock type. The presence of Biwabik Iron Formation as inclusions, from the Birch Lake deposit to as far north as the Spruce Road deposit, indicates that the majority of Paleoproterozoic units were assimilated and removed from the footwall during emplacement of the South Kawishiwi intrusion (Severson et al., 2002). The basal stratigraphic section of the SKI is known in great detail from studies of abundant drill core and is subdivided into 17 different units (Fig. 5-7) that are present over a strike-length of 19 miles (31 kilometers). The lowermost units are unevenly distributed along the strike length of the intrusion in a “compartmentalized” fashion, suggesting a complicated intrusive history (Miller and Severson, 2002). A few salient features to keep in mind regarding the igneous stratigraphy of the SKI include:

- The vast majority of sulfide mineralization is confined to the BH (Basal Heterogeneous Unit), BAN (Basal Augite Troctolite and Norite Unit), UW (Updip Wedge Unit), and U3 (Ultramafic 3 Unit) – the latter three of these units are combined and referred to as the BMZ (Basal Mineralized Zone) by Twin Metals at their Maturi deposit;

- Major marker beds, at specific areas in the SKI, include three horizons that contain abundant cyclic ultramafic layers (U1, U2, and U3 Units) and a pegmatite-bearing unit (PEG Unit - originally recognized by Foose, 1984). The U1, U2 and U3 Units represent periods of rapid and continuous magma replenishment that crystalized more primitive ultramafic layers before mixing with the resident magma (Severson et al., 2002);
• The U3 Unit is unique in that it contains several massive oxide pods (titanomagnetite-rich), as well as, recognizable inclusions of bedded Biwabik Iron Formation; especially at the Birch Lake deposit. The spatial correspondence between the U3 Unit and footwall iron-formation suggests that most of the massive oxide pods are iron-rich “restite” produced by assimilation and partial melting of the iron-formation (Muhich, 1993; Severson, 1994; Severson et al., 2002);

• The U3 Unit contains the vast majority of high PGE values, especially within the Birch Lake area and possibly at the Maturi deposit. However, high PGE values are also present in the PEG Unit (Birch Lake area and Maturi deposit), the top of the BH Unit (Maturi deposit), and very locally in troctolitic rocks situated well above the basal contact (South Filson Creek deposit); and

• A large inclusion/pillar of anorthosite is present at the Maturi deposit. This pillar, and possible proximity to a vent area and magma flow paths (see discussion for Maturi deposit) are the inferred reasons for high PGE values at the Maturi deposit.

**REGIONAL ECONOMIC GEOLOGY**

By: Richard Patelke and Dean Peterson

While Minnesota is home to the United States iron ore industry, development of its known non-ferrous deposits has been hampered by industry downturns, remoteness from the rest of the base metals industry, a complex land situation, and a (wrongly) perceived environmental risk. The state has done much to support non-ferrous exploration, in particular maintaining an impressive drill core and data library in Hibbing, and sponsoring extensive mapping and sampling projects. Research arms of the MDNR and the University have contributed much knowledge to mineral processing methods for these ores. In general this work has not been well publicized. This short discussion on regional mineral potential focuses on rocks in the north part of the state, but there has been recent exploration for nickel and diamonds throughout the state. For detailed discussion of potential in Archean rocks see Peterson (2001a) and for Duluth Complex rocks see Miller et al., 2002.
Mesabi Range Iron Mines-Status
There are six operating iron mines employing about 4,200 people in the region (plus 13,000 indirect jobs). These mines contribute about $1.8 billion to the economy of Minnesota with an added $1.6 billion indirect contribution. All of the mines produce taconite pellets from low grade magnetic ore. Four mines are captive to steel companies, and two produce pellets for market, generally through long term contracts. Product shipping is largely by rail to one of four ports on Lake Superior, then by boat to mills on the lower Great Lakes. The mines are capable of producing over 40 million tons annually. Total material movement (ore and stripping) is on the order of two hundred million tons. The one-hundred plus year history of this world class mining district means that there is an extensive developed infrastructure and service industry for these mines.

Three iron related projects are in various phases of development in 2013: Mesabi Nugget, located near the PolyMet plant site, uses purchased concentrate, and hematite concentrate obtained from old stockpiles and tailings basins, to produce iron nuggets suitable for electric furnace production of steel – they began production in 2009; Magnetation produces hematitic concentrates from old direct ore stockpiles and tailings basins; and Essar Steel (Minnesota Steel Industries, formerly Minnesota Iron & Steel) plans to re-open a closed taconite mine (Butler Taconite) at the western end of the Mesabi Range and produce direct reduced iron from taconite pellets on site.

Other Regional Economic Geology
Two broad age groups dominate the other rocks with mineral potential in northern Minnesota. Archean rocks represent possible hosts for lode gold, Volcanogenic Massive Sulfide (VMS), and diamond prospects. North of the Duluth Complex is extensive terrane of exposed Archean rock, similar to that in Ontario (Wawa and Quetico subprovinces). Over the years various prospects for gold and base metals have been delineated, but follow up work has been sporadic and generally short lived. These prospects include, for gold: Raspberry, Murray Shear zone, Spaulding Bay, Mud Lake, Pac Man Pond, and Section 6, investigated by Goldfields, Newmont, Kerr McGee, and Noranda among others. For base metals the deposits include: Clear Lake, Skeleton Lake, Fivemile Lake, and Purvis Road worked by the above companies as well as Exxon, Teck, Rendrag, and Lehmann. A 2001 PhD. thesis (Peterson, 2001a) is an excellent review of the Archean mineral potential of the region. That report makes detailed analytical comparisons between producing gold and base metals camps in Canada and prospects in Minnesota. Diamond work in Archean age rock of Minnesota includes Exmin (DeBeers), WMC, and others; as well as the Minnesota Geologic Survey.

Proterozoic rocks in northern Minnesota include Animikie Basin (Paleoproterozoic, ~1.8 Ga) sedimentary rocks (Pokegama Quartzite, Biwabik Iron Formation, and the Virginia Formation). Besides current iron ore production, very limited exploration has focused on zinc and other base metals in the Virginia Formation. Anomalous mineralization ( sphalerite, molybdenite) has been found in the Virginia, but no prospects have been defined.

Titanium and Other Oxide Mineral Potential in the Duluth Complex
There are at least four titanium deposits within 12 miles (19 kilometers) of PolyMet’s Hoyt Lakes plant site (out of 13 known titanium deposits in the area). They are all located in the Duluth Complex and are called “OUI’s” for “Oxide Ultramafic Intrusions” (Severson and Hauck, 1990). These are titanium rich plugs that cross-cut the rocks of the Duluth Complex. All are greatly under sampled, especially for PGE and other oxides besides titanium (chromium, vanadium, etc.)

Bulk samples have been processed from one of these titanium prospects. The titanium in these deposits is in magnesium-rich ilmenite which is not easily processed by current commercial methods. BHP, Coleraine Minerals Research Laboratory of the NRRI, and others have done extensive process testing towards adding value to these prospects. All 13 have been drilled, but generally not to a point where a
legitimate (i.e., NI43-101 compliant) resource can be declared. Three OUI’s with reasonable resource estimates are:

1. **Longnose** with a NI43-101 indicated resource of 58.1 million tons averaging 16.6% TiO₂ (inferred 65.3 million tons averaging 16.4% TiO₂) based on 27 drill holes and using a cut off grade of 8% TiO₂;
2. **Titac** (formerly known as Section 34) with a NI43-101 inferred resource of 45.1 million tons averaging 14% TiO₂ based on 32 drill holes and using a cut off grade of 8% TiO₂; and
3. **Water Hen** with a crudely estimated 62 million tons averaging 14% TiO₂ based on 37 drill holes. Note that at present, Cardero Resources has leased Longnose and Titac (Section 34 deposit).

Overall, the “plug-like” OUIs could represent great potential for undiscovered copper-nickel-PGE, as well as oxide potential (titanium, chromium, vanadium, etc). There is a large collection of core, and related data, stored at the Minnesota Department of Natural Resources in Hibbing. The NRRI has logged most of this core, and consolidated whatever assay data is available (Patelke, 2003).

**PART 5A: POLYMET NORTHMET DEPOSIT**

By: the late Richard Patelke with modifications by Andrew Ware

**NORTHMET PROJECT SUMMARY**

NorthMet, located in the Partridge River intrusion of the Duluth Complex, is a large, disseminated sulfide deposit in heterogeneous troctolitic rocks associated with the 1,100 million year old Mid-Continent rift. Metals of interest are copper, nickel, cobalt, platinum, palladium, and gold. The majority of the metals are concentrated in four sulfide minerals: chalcopyrite, cubanite, pentlandite, and pyrrhotite, with platinum, palladium and gold also found in bismuthides, tellurides, and alloys. NorthMet is one of eleven copper-nickel-PGE deposits along the northern margin of the Complex (PGE: platinum, palladium, gold). All of these share grossly similar geologic settings–disseminated sulfides with minor local massive sulfides in heterogeneous rocks forming the basal unit of the Duluth Complex along the contact with older rocks.

The deposit is on the southern flank of the Mesabi Iron Range, which is host to six large operating taconite mines, the closest of which is less than two miles (3.2 km) north of the planned NorthMet pits (Figure 5A-1). Ore from NorthMet will be processed at a rate of 32,000 short tons per day through the former LTV Steel Mining Company iron ore concentration plant (“Eric Plant) with new facilities for processing of the NorthMet copper-nickel-PGE concentrates through a hydrometallurgical method day to produce copper metal and various hydroxide and concentrate products of nickel-cobalt-PGE (Fig. 5A-2).

**EXPLORATION and DEVELOPMENT**

There have been four major drilling programs since 1969, re-sampling for PGE began in 1989, three PolyMet joint ventures were pursued and dissolved in the 1990's, processing technology was developed in the late 1990's, the former LTV Steel Mining Company concentrator and other property was optioned in 2003, and the metallurgical process was refined in 2005-2008.

Drilling programs have been conducted by United States Steel (USS, 1969-1974) and PolyMet Mining Inc. (Reverse Circulation or “RC” drilling and core drilling in 1998-2000 & two phases of core drilling in 2005 and 2007), plus two (actually two pairs of twins) holes by NERCO Minerals Company in 1991. This drilling encompasses 285,756 feet over 371 holes as of May 2008. Over 35,973 acceptable assays have been taken from this drilling (216,344 feet assayed). Table 5A-1 gives a breakdown of years, footages, and number of assays for all project drilling.
United States Steel (USS) began core drilling at NorthMet (as the Dunka Road project) in 1969. Drilling targeted a conductor that turned out to be in the footwall metasedimentary rocks, but the first drill hole hit massive sulfide in the Duluth Complex. Drilling continued over five years for 112 holes with 133,716 feet of intercept. The working assumption was to mine the deposit from underground, sampling was limited to the most continuous zones with strong visible copper-nickel mineralization, and only about 2,200 samples representing about 22,000 feet were taken. USS assayed only for copper, nickel, sulfur, and iron. PGE presence was known from sampling on concentrates, but the economics of PGE recovery were apparently not pursued. Project work stopped while apparently incomplete and was not restarted.

USS did not do much follow-up, but kept their land ownership, core, pulps, coarse rejects, and records for the project. In the mid 1980's the Minnesota Department of Natural Resources (MDNR) began sampling various historic drill core intervals in the Duluth Complex for PGE and got some good, but localized, results. In 1989 Fleck Resources (Fleck) leased the Dunka Road property from USS and began a program of re-assaying USS pulps and coarse rejects with a much more extensive multi-element suite, as well as adding in some new samples from existing core through cooperative work with the Natural Resources Research Institute (NRRI), associated with the University of Minnesota Duluth. The results were very positive in showing elevated PGE values in the deposit and confirming the previous copper-nickel assays.

Fleck partnered with NERCO in 1991 for some bulk sample work, mine plans, environmental reviews etc., done through Fluor Daniel Wright engineers, but the partnership was eventually dissolved. In 1995 Fleck joined with Argosy Mining Corp. to do more work on the project, again with no major progress towards production. In June 1998, Fleck became PolyMet and focused their resources on Dunka Road, which was renamed NorthMet. Without partners, except for a brief venture with North Mining (North), PolyMet drilled and sampled 87 holes in 1998-2001, and sent two large bulk metallurgical samples to Lakefield Laboratories (now SGS) in Lakefield, Ontario for development and refinement of the PlatSol hydrometallurgical process and began some environmental background work.

In the summer of 2000, North was taken over by Rio Tinto. The joint venture agreement was terminated by PolyMet upon consideration that NorthMet appeared to be a low priority to Rio Tinto. The main concern was that other partnership opportunities might be missed during the time that Rio Tinto assessed and prioritized the ongoing North projects. However, much of the North funding was already in place and was used to partially finance the 2001 pre-feasibility study. After release of the pre-feasibility study (2001), a brief hiatus, and a major re-evaluation of how the project should proceed, PolyMet became active again in 2003 with new management and a new development plan.

This plan involves integrating the former LTV Steel Mining Company iron ore concentration plant (“Erie Plant) with new facilities for processing of the NorthMet copper-nickel-PGE concentrates through a hydrometallurgical method at rate of 32,000 short tons of ore per day to produce copper metal and various hydroxide and concentrate products of nickel-cobalt-PGE. Geologic work towards this end began in 2004 and first focused on a careful and total re-compile of the historic NorthMet project drill hole related data. This effort organized and verified all drilling metadata, location, downhole survey, lithology, and assay data, and cataloged all paper (and digital) records for the project. Of note is that this resulted in an increase in the number of acceptable assays from 12,000 to around 17,200 and an improved geologic picture from careful consolidation of existing records.

This work was used as background for a revised resource estimate in January 2005 and planning of a drill program for 2005. The 2005 program entailed drilling and sampling 109 holes (77,000 feet), collection of a forty ton metallurgical bulk sample for pilot scale testwork, geotechnical (oriented core) drilling, in-fill sampling of previously drilled core, and extensive collection of waste characterization data. The 2005 drilling program added 13,450 multi-element assay records to the existing database. A PolyMet report covers the details of historic drilling and assaying (Patelke & Geerts, 2006).
Figure 5A-1. PolyMet NorthMet project site.
Figure 5A.2. Detail of Erie Plant site showing existing facility and new construction.
Drilling in 2007 for 24,530 feet with 3,546 assays concentrated on defining mineralization in the upper units in the west part of the deposit (the “Magenta Zone”). This drilling and the subsequent re-modeling of the deposit turned about 50 million tons of material previously classed as waste to ore. There is also over 34,000 feet of hydrogeology drilling and “stratigraphic holes” (drilling by other companies not done as part of the NorthMet project). No assays are in use from these 44 holes which are used for geologic control. Approximately 89.5% of Unit 1 and about 57% of the upper units have been sampled across the deposit. The sampled percentages are higher in the anticipated area of mining.

<table>
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<th>Assaying years</th>
<th>No. of drill holes</th>
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<td>61</td>
<td>24,530</td>
<td>3,456</td>
<td>23,310</td>
<td>ALS-Chemex</td>
</tr>
<tr>
<td><strong>Totals for Exploration Drilling:</strong></td>
<td><strong>371</strong></td>
<td></td>
<td><strong>285,756</strong></td>
<td><strong>35,973</strong></td>
<td><strong>216,344</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>US Steel stratigraphic holes</td>
<td>1970's?</td>
<td>none</td>
<td>6</td>
<td>9,647</td>
<td>none</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>INCO</td>
<td>1956</td>
<td>none</td>
<td>3</td>
<td>2,015</td>
<td>none</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>Humble Oil / Exxon</td>
<td>1968-1969</td>
<td>none</td>
<td>3</td>
<td>9,912</td>
<td>none</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>Bear Creek / AMAX</td>
<td>1967-1977</td>
<td>none</td>
<td>11</td>
<td>8,893</td>
<td>none</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>PolyMet / Barr Engineering (hydrologic testing)</td>
<td>2005-2007</td>
<td>none</td>
<td>21+</td>
<td>3,459+</td>
<td>none</td>
<td>none</td>
<td>none</td>
</tr>
</tbody>
</table>
**Table 5A-2. Large metallurgical samples collected at NorthMet**

<table>
<thead>
<tr>
<th>Bulk Sample</th>
<th>Year</th>
<th>Tons</th>
<th>Location of sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>USS Bulk sample pit No. 1</td>
<td>1971</td>
<td>Unknown, but small</td>
<td>Pit in center of property</td>
</tr>
<tr>
<td>USS Bulk sample pit No. 2</td>
<td>1971</td>
<td>300</td>
<td>Pit at east end of property</td>
</tr>
<tr>
<td>USS Bulk sample pit No. 3</td>
<td>1971</td>
<td>20</td>
<td>Pit at east end of property</td>
</tr>
<tr>
<td>NERCO PQ drill core</td>
<td>1991</td>
<td>Estimated at 4.5 tons or less by drill core size</td>
<td>One PQ drill hole from each end of property</td>
</tr>
<tr>
<td>Argosy Mining</td>
<td>1995</td>
<td>Unknown, but small</td>
<td>Composited from USS coarse rejects</td>
</tr>
<tr>
<td>PolyMet RC drill cuttings</td>
<td>1998</td>
<td>26</td>
<td>One composite, mostly from what is now considered east part of 10 year pits</td>
</tr>
<tr>
<td>PolyMet RC drill cuttings</td>
<td>2000</td>
<td>33</td>
<td>One composite, mostly from what is now considered east part of 10 year pits</td>
</tr>
<tr>
<td>PolyMet 4 inch and PQ core and coarse reject</td>
<td>2005</td>
<td>10.5, 21.5, and 10.7</td>
<td>Three composites from within ten year pits across property</td>
</tr>
<tr>
<td>PolyMet coarse reject</td>
<td>2006</td>
<td>4.2 and 4.94</td>
<td>One composite from 10 year east pit, one from 20 year pit across property</td>
</tr>
<tr>
<td>PolyMet ¼ core from 2005 and 2007 Drilling</td>
<td>2007</td>
<td>500 kg</td>
<td>One composite, from east and west pit areas</td>
</tr>
<tr>
<td>PolyMet ¼ core from 2005 and 2007 Drilling</td>
<td>2008</td>
<td>4.44</td>
<td>One composite, from east and west pit areas</td>
</tr>
<tr>
<td>PolyMet ¼ core from 2005 and 2007 Drilling</td>
<td>2008</td>
<td>4.48</td>
<td>One composite, from east and west pit areas</td>
</tr>
</tbody>
</table>

Sampling in Unit 1 (the main mineralized zone) is now mostly continuous through the zone for all generations of drilling. The PolyMet RC and core holes have continuous sample through the upper waste zones (which do have some intercepts of economic mineralization). Work in 2005 through 2008 essentially completed the sampling of historic USS core within the area likely to be mined. This broad sampling limits the possibility of location bias in the sample set. While not all of the USS core has been sampled, there is no known unsampled mineralized core.

There have been numerous bulk samples taken at NorthMet (Table 5A-2). Samples have been representative by Unit and rock type. Agreement between calculated grades (based on core sampling) and analyzed grades of final sample has been excellent. Earlier bulk samples represented the first ten years of production, more recent samples used material from across the deposit. Each bulk sample has built upon the previous, and work has progressed to the point where PolyMet has confirmed the ability to make separate, saleable, copper and nickel concentrates. This will allow the company to develop cash flow from sales much earlier in production while completing construction of the hydrometallurgical facility.

The planned hydrometallurgical process (PlatSol) was developed on NorthMet ores. The process uses pressure oxidation (225°C, over 30 atmospheres) in the presence of chloride to capture all base and precious metals in the concentrate. Hydromet process recoveries are all over 98%. Other geologic data collected includes: recovery and RQD measurements on all core, over 7,000 specific gravity measurements, over 900 whole rock analyses, over 300 Rare Earth Element packages and a large amount of microprobe data collected for waste characterization purposes.
GEOLOGY OF THE NORTHMET DEPOSIT

NorthMet consists of seven igneous units that dip southeast, with most economic sulfide mineralization in the top parts of the lowermost unit (Unit 1). The following is a summarized description of the geology of the deposit, based on observations from drill core and limited outcrop mapping.

Quaternary Geology
In general the Quaternary geology of the region is a thin (0-30 feet or 0-10 meters., but locally thicker) blanket of glacial deposits including till, lacustrine materials, and outwash. Low spots are usually peat bog or open wetland. Topography is subdued and drainage is poor. Site specific geologic studies of the drift have not been done, though a series of geophysical soundings were carried out in 2006 to better define drift thickness outside the area to be mined (Ikolaha, 2006). Lehr and Hobbs (1992) mapped the area as part of the Wampus Lake Moraine. Minnesota Geologic Survey map 164 (Jennings and Reynolds, 2005, includes GIS database) categorizes all drift materials as Rainy Lobe till and re-sedimented glacial deposits, overlain locally by post glacial peat.

Test pits for preliminary PolyMet engineering studies and informal observations of sumps and other small excavations bear this out. Most areas consist of unsorted sand / silt / clay with cobbles and boulders. Boulders on surface can be greater than 10 feet in size and there may be a boulder lag horizon just below the ground surface in some areas. As measured from drill holes, thickness of the drift ranges from 0 to 50 feet (mostly less than 20 feet) and averages about 12 feet. The 2006 geophysical soundings measured thicknesses up to 60 feet past the western margins of the drilled area.

Structural Geology
The general structure of the NorthMet deposit, as defined by igneous contact dips, foliation in serpentinized zones, bedding trends in the Biwabik Iron Formation (BIF) and in the Virginia Formation, is dominated by an overall dip ranging from 15-25° to the southeast, striking about N56°E. Dips in the seven igneous units are grossly similar, but dips of the mineralized zone are up to 60° in the east pit area. Dips in both the Animikian and the Duluth Complex rocks can be attributed to crustal loading, associated with the input of large volumes of magma originating from the Mid-continent Rift System (Sims and Morey, 1972).

Numerous faults have been proposed across the NorthMet Deposit, based largely on reconciling dips in the footwall rocks. Unfortunately, not enough evidence has been established through drilling to indicate with certainty the exact location of major offsets or faulting within the igneous rock units or the footwall rocks on a hole-to-hole basis. This definition difficulty is compounded by the fact that over time the fault representations have been extended vertically from ground surface to footwall, though many were originally thought to only show offset in the footwall, or were based solely on limited outcrop evidence.

Clearly however, offset or faulting exists, at least within the footwall rocks, due to substantial offsets in the BIF (assuming an average 20° dip) as evidenced between drill holes portrayed in cross-sections. Many of these same offsets can be correlated in adjacent cross-sections. Fault zones are apparent in drill core and show up as brecciated intervals (up to several feet thick), including gouge mineralization (clay, calcite, quartz, etc.), slickensides on serpentinized fracture faces, and/or severely broken (rubble) core. However, the exact location of all faults/offsets at the NorthMet Deposit on a hole to hole basis has only been approximated, due to the sparse structural information as so far provided by drilling. Extensive angle drilling in 2005 and 2007 (142 of 170 holes) brought no great clarity to this issue (virtually all previous drilling was vertical). The current geological model and working cross-sections are therefore constructed with minimal faulting influence, especially within the igneous rock units of the Partridge River intrusion, until more evidence clarifies this issue.
Logging and Mapping Units
A summary of the general stratigraphy of the NorthMet Deposit is outlined below. Rock units and formations are listed in descending order, as would be observed from top to bottom in drill hole. NorthMet units are labeled as Units 1 through 7 (Units I through VII in Severson’s terminology), bottom to top. Unit 3 is probably the oldest, the intrusion sequence of the other units is not clear.

The broad picture is of a regular stratigraphy of troctolitic to anorthositic rock units, dipping southeast at 20° to 25°, with basal ultramafic units defining the boundaries of some of these units. The basal ultramafic zones tend to have diffuse tops, sharp bases, and are commonly serpentinized and foliated. Geologists have generally picked the unit boundaries at the base of these ultramafics though there are local exceptions. Economic sulfide mineralization is ubiquitous in the basal igneous unit (Unit 1) and is locally present, but restricted, in the upper units.

Unit Definitions and Descriptions
Descriptions of the general igneous Stratigraphy for the NorthMet deposit is described below and presented in a stratigraphic column in Figure 5A-3.

Unit 7
Unit 7 (Figures 1-9, 1-10, and 1-11) is the uppermost unit intersected in drill holes at the NorthMet Deposit. It consists predominantly of homogeneous, coarse-grained anorthositic troctolite and troctolitic anorthosite, characterized by a continuous basal ultramafic subunit that averages 20 ft. thick. The ultramafic consists of fine- to medium-grained melatroctolite to peridotite and minor dunite. The average thickness of Unit 7 is unknown due to erosion removing the upper parts. Unit 7 is generally not mineralized.

Unit 6
Very similar to Unit 7, Unit 6 is composed of homogeneous, fine- to coarse-grained, troctolitic anorthosite to troctolite. It averages 400 ft. thick and has a continuous basal ultramafic subunit that averages 15 ft. thick. Overall, sulfide mineralization is minimal, although a number of drill holes in the southwestern portion of the NorthMet Deposit contain significant sulfides and associated elevated PGEs (Geerts 1991, 1994). Sulfides within Unit 6 generally occur as disseminated chalcopyrite/cubanite with minimal pyrrhotite. This mineralized occurrence, the “Magenta Zone”, transitions into Units 3, 4, and 5, and is discussed in greater detail below.

Unit 5
Unit 5 exhibits an average thickness of 250 ft. and is composed primarily of homogeneous, equigranular-textured, coarse-grained anorthositic troctolite. Anorthositic troctolite is the predominant rock type, but can locally grade into troctolite and augite troctolite towards the base of the unit. The lower contact of Unit 5 is gradational and lacks any ultramafic subunit, therefore the transition into Unit 4 is a somewhat arbitrary pick. Due to the ambiguity of this contact, thicknesses of both units vary dramatically. However, when Units 5 and 4 are combined, the thickness is fairly consistent deposit-wide. Aside from Magenta Zone mineralization in the west, Unit 5 is not mineralized.

Unit 4
Being somewhat more mafic than Unit 5, Unit 4 is characterized by homogeneous, coarse-grained, ophitic augite troctolite with some anorthosite troctolitic. Unit 4 averages about 250 ft. thick. At its base, Unit 4 may contain a local thin (usually no more than 6 inch) ultramafic layer or oxide-rich zone. The lower contact with Unit 3 is generally sharp. Unit 4 is rarely mineralized outside the Magenta Zone.
Unit 3
Unit 3 is used as the major “marker bed” in determining stratigraphic position in the PRI. It is composed of fine- to medium-grained, poikilitic and/or ophitic, troctolitic anorthosite to anorthositic troctolite. Characteristic poikilitic olivine gives the rock an overall mottled appearance. On average Unit 3 is 300 ft. thick. As with Units 4 and 5, the thickness of Units 2 and 3 tend to be highly variable, whereas if combined into one unit, it is more consistent deposit-wide (though not as consistent as Units 4 & 5).

Unit 2
Unit 2 is characterized by homogeneous, medium- to coarse-grained troctolite and augite troctolite with a consistent basal ultramafic subunit. The continuity of the basal ultramafic subunit, in addition to the relatively uniform grain size and homogeneity of the troctolite, makes this unit distinguishable from Units 1 and 3. Unit 2 has an average thickness of 100 ft. The ultramafic subunit at the base of Unit 2 is the
lowermost continuous basal ultramafic horizon at the NorthMet Deposit, averages 25 ft. thick, and is composed of melatroctolite to peridotite and minor dunite.

In some ways the characteristics of Unit 2 and how it fits into the stratigraphy are ambiguous. It can be interpreted as the lower part of Unit 3, the upper part of Unit 1, or a separate unit. Based on continuity of the ultramafic boundary it seems to be a lower, more mafic, counterpart to Unit 3 or a separate unit. However, even though Unit 2 has been historically described as barren, in the western part of the deposit it appears to have mineralization grossly continuous with that at the top of Unit 1. The general lack of footwall inclusions would argue against Unit 2 being older than Unit 1.

**Unit 1**

Of the seven igneous rock units represented within the NorthMet Deposit, Unit 1 is the only unit that contains significant deposit-wide sulfide mineralization. Sulfides occur primarily as disseminated interstitial grains between a dominant silicate framework and are chalcopyrite > pyrrhotite > cubanite > pentlandite. Unit 1 is also the most complex unit, with internal ultramafic subunits, increasing and decreasing quantities of mineralization, complex textural relations and varying grain sizes, and abundant sedimentary inclusions. It averages 450 ft. thick, but is locally 1,000 feet thick and is characterized lithologically by fine- to coarse-grained heterogeneous rock ranging from anorthositic troctolite (more abundant in the upper half of Unit 1) to augite troctolite with lesser amounts of gabbro-norite and norite (becoming increasingly more abundant towards the basal contact) and numerous sedimentary inclusions. By far the dominant rock type in Unit 1 is medium-grained ophitic augite troctolite, but the textures can vary wildly. Two internal ultramafic subunits occur in drill holes in the southwest, and have an average thickness of 10 ft.

*Footwall rocks are covered in the Partridge River intrusion description.*

**Inclusions**

Two broad populations of inclusions occur at NorthMet: hanging wall metabasalts (Keweenawan) and footwall metasedimentary rocks. Basalts are fine-grained, generally gabbroic, with no apparent relation to any mineralization. Footwall inclusions may carry substantial sulfide (pyrrhotite) and often appear to contribute to the local sulfur content. Footwall inclusions are all Virginia Formation, no iron-formation, Pokegama Quartzite, or older granitic rock has been recognized as an inclusion at NorthMet. Sedimentary inclusions make up about 4% of the logged rocktypes, and basalt inclusions sum to less than 1% of the drilling footage.

**Inclusions and Timing**

Generally, hanging wall inclusions are restricted to Unit 3 and the units above, while footwall inclusions are most abundant in Unit 1. This zoned distribution of inclusions indicates that one possible scenario for order of intrusion is that Unit 3 intruded first, created space between the basalt and the Virginia Formation, then portions of the hanging wall basalts collapsed into the Unit 3, but for some reason Unit 3 was not able to disassemble or assimilate much of the footwall rock (due to temperature, viscosity of magma or ductility of the footwall). Unit 1 however, intruded between Unit 3 and the footwall and was able to assimilate large portions of the footwall and thus contaminate itself with both sulfur and silica. In this scenario Unit 2 is intruded after Unit 1, between Units 1 and 3, as Unit 2 has limited footwall inclusions. Unit 3's intrusion would have separated the footwall and Unit 1 from later Units 4 through 7, which never reacted with the footwall at the NorthMet site. Therefore, any footwall inclusions seen in Units 4 through 7 (and probably those seen in Unit 2) can be interpreted as being carried in from some other part of the magmatic system. Note that basalt overlies and is in direct contact with the Virginia Formation at the Wetlegs deposit to the west of NorthMet, implying that the starting conditions for this chain of events are plausible.
Other Igneous Units
Quadangle scale outcrop mapping indicates that other igneous stratigraphic units are present above Unit 7. These units are similar to Units 6 and 7 in that they consist of homogeneous-textured troctolitic rocks with basal ultramafic members.

There are minor, unmineralized, pre-Complex sills in both the Virginia Formation and Biwabik Iron Formation at NorthMet (VirgSill and BIF Sill in footwall descriptions above). In neither case is there any apparent relation to Duluth Complex mineralization. Early sills in the Virginia probably metamorphosed the Virginia, forming a zone that resisted assimilation during later intrusion of the Complex—hence leading to the thin “rind” of metamorphosed Virginia on top of the BIF seen in the deeper downdip drill holes at NorthMet.

Alteration
The vast majority of rock within the NorthMet Deposit would be considered fresh and is unaltered or only weakly altered. Types of alteration most commonly observed in NorthMet rocks are serpentinization / chloritization of olivine, sericitization and saussuritization of plagioclase, and uralitization of pyroxenes. Most alteration is related to close proximity of fractures and/or joints that cross-cut the troctolitic rocks. Likewise, on a microscopic level the center of alteration is focused around microfractures. This pattern suggests that both fracturing and accompanying alteration of the rock occur as a result of the migration of late-stage deuteric fluids during the cooling phase. The vast majority of sulfide mineralization is independent of alteration.

Nickel in Silicates (Lab Assay Nickel vs. Recoverable Nickel)
It has been characteristic of NorthMet and other Duluth Complex deposits to show lower nickel recoveries in process test work than would be expected from laboratory assays on drill core. Generally there is a loss of about 25-35% of the nickel compared to drill core assays when concentrating sulfides. From previous work, it is known that small amounts of unrecoverable nickel occur as a magnesium-iron-nickel silicate [\((\text{Mg,Fe,Ni})_2 \text{SiO}_4\)] that is tied up in the mineral olivine, which is one of three significant gangue minerals that occur across the NorthMet deposit. Testwork has shown that most of the very small amount of nickel contained in silicates would not be recovered during the autoclaving process proposed.

For example, mineralogical studies show that approximately 25% to 35% of the rock in NorthMet is composed of olivine. Previous microprobe study, plus work by PolyMet in 2006, has shown an average of about 0.10% nickel in olivine. The approximate nickel grade of the PolyMet metallurgical bulk samples is 0.10%. Because the average nickel in the olivine is the same as the average nickel in the bulk samples, the unrecoverable nickel in the olivine would be expected to reduce nickel recovery by the amount of olivine in the bulk sample - 25% to 35%. Nickel recoveries on the six PolyMet metallurgical bulk samples have ranged from 69% to 77%. This is in line with an approximate 25% to 35% loss of nickel to silicate.
Figure 5A-4. Geologic map of NorthMet Deposit, all units dip southeast, Magenta Zone is projected upward, does not actually subcrop.
Figure 5A-5. Cross section 35700 at west end of property and 45600 at east end. Purple shading indicated ore zones, bar graphs along holes indicate grades expressed as dollar values, where red = $7.42 cut-off to average grade (~$14.39), and purple shows above average grade, blue are zones of potential lean ore should metals prices rise.
ECONOMIC MINERALIZATION

The majority of economic mineralization (copper, nickel, cobalt, platinum, palladium, and gold) at NorthMet occurs in the upper parts of basal Unit 1, with copper and nickel in chalcopyrite, cubanite, and pentlandite, all in the presence of pyrrhotite. Cobalt is contained in sulfides. Platinum, palladium, and gold, while showing good correlation with sulfur and the other metals, are also in a variety of tellurides, bismuthides, and alloys, as well as associated with the major and minor sulfides. Table 5A-3 shows correlation of metals values in drill core data.

Table 5A-3. Simple correlation table for economic metals and sulfur

<table>
<thead>
<tr>
<th></th>
<th>Cu %</th>
<th>Ni %</th>
<th>S %</th>
<th>Pt ppb</th>
<th>Pd ppb</th>
<th>Au ppb</th>
<th>Pt+Pd+Au</th>
<th>Co ppm</th>
<th>Zn ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu %</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ni %</td>
<td>0.860</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S %</td>
<td>0.541</td>
<td>0.572</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pt ppb</td>
<td>0.568</td>
<td>0.508</td>
<td>0.195</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pd ppb</td>
<td>0.750</td>
<td>0.635</td>
<td>0.292</td>
<td>0.673</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Au ppb</td>
<td>0.591</td>
<td>0.472</td>
<td>0.250</td>
<td>0.482</td>
<td>0.699</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pt+Pd+Au</td>
<td>0.760</td>
<td>0.645</td>
<td>0.292</td>
<td>0.778</td>
<td>0.983</td>
<td>0.755</td>
<td>1.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Co ppm</td>
<td>0.544</td>
<td>0.704</td>
<td>0.621</td>
<td>0.217</td>
<td>0.281</td>
<td>0.241</td>
<td>0.288</td>
<td>1.000</td>
<td></td>
</tr>
<tr>
<td>Zn ppm</td>
<td>-0.021</td>
<td>-0.004</td>
<td>0.286</td>
<td>-0.041</td>
<td>-0.037</td>
<td>-0.017</td>
<td>-0.039</td>
<td>0.093</td>
<td>1.000</td>
</tr>
</tbody>
</table>

The simple correlation table above (number of samples=19,516) shows the strong relation of copper, nickel, and palladium, and a somewhat surprising relation of cobalt to sulfur. Zinc’s low factor is probably related to its multiple origins as either magmatic or derived from assimilation of footwall rock, hence representing two populations of data. The sulfur vs. metal correlation is probably greatly affected by iron, the presence of which is not shown here, but is in excess in all rocks.

Grades are highest at the top of Unit 1 and fade going down hole. Grades appear to be higher down-dip though this may be an artifact of less dense sampling. There is a smaller zone of economic mineralization (about 50 million tons) at the western end of the property in the upper units, known as the “Magenta Zone.” This zone is generally copper and PGE-rich (sulfur-poor relative to metals) and of “average” reserve grade.

The minerals of interest from a waste characterization perspective are the same as above, but pyrrhotite is expected to be the main mineral affecting water quality in regards to waste rock, though the traces of chalcopyrite, cubanite and pentlandite will require study for waste rock storage. Trace pyrite and pyrrhotite are the main sulfide minerals found in the tailings. Pyrite is largely from joint faces and other secondary sources-it is rarely seen in polished section or core.

Most sulfide mineralization at NorthMet is of a distant source (but sedimentary?), some is locally modified by sulfur derived from footwall metasedimentary rocks (Virginia Formation). Minor veins and other cross-cutting relations indicate some movement of sulfides within the deposit, but there is no evidence recognized for large scale relocation of sulfides, nor any macroscopic evidence for any hydrothermal event that may have remobilized PGE’s or sulfides.

Virtually all sulfide mineralization at NorthMet moved in with magmatic pulses, and metal enrichment of the magma happened in a deeper chamber. Therefore, the main controls on the location of mineralization within the deposit may be the specific magmatic pulse or pulses making up the individual units. While
Textures in Unit 1 are described as heterogeneous, there is also a broad homogeneity in regards to mineral occurrence, mineral chemistry, whole rock and REE chemistry, and gross rock type that all reinforce the view of a large system of magma pulses replenishing the resident magma at the NorthMet site.

The exception to this is that some sulfur, particularly in Unit 1, was derived locally from assimilation of footwall rocks (evidenced by high pyrrhotite content nearer footwall inclusions). The main effect of this assimilation has been to dilute the sulfide grade with additional pyrrhotite in Unit 1, rather than this sulfur scavenging more base metals from the magma.

**RESOURCE**

The PolyMet resource and reserve (Table 5A-4) models have been done in cooperation with several consultants, most recently PEG Mining of Toronto. PolyMet supplies the geologic solids model, database, and block model geometry. Geostatistics and population of the block model, and hence the resource estimate, are done in consultation, with finalized resource block models then sent forward to engineers for reserve calculation and mine planning. Resource geologic modeling treats the NorthMet deposit as five separate domains:

1. Virginia Formation footwall rocks;
2. a domain including the upper, higher grade parts of Unit 1, locally merged with the higher grade zones at the base of Unit 2;
3. the remainder (lower part) of Unit 1;
4. the Magenta zone in Units 3, 4, 5, & 6 in the western part of the deposit;
5. and the remaining, less mineralized, parts of Units 2 through 7.

Unit 1 is mineralized throughout the deposit area, with other units (2 through 6) showing some economic mineralization in the western and central parts of the deposit, but essentially no continuous zones in the east. There is no known economic mineralization in the footwall rocks. Deposit wide, Unit 1 has the highest grades near its top.

Though grades vary, Unit 1 is also mineralized to the east of the deposit, down-dip (south) to depths of at least 2,500 feet, and past the limits of expected pit development in the west. The development of waste rock stockpiles over these areas in the east and south is not expected to encumber any material that could reasonably be classed as ore because the upper units are barren and the Unit 1 mineralization is from 1,700 to over 2,500 feet below ground surface.

For modeling purposes, Unit 1 is bounded by both “hard” and “soft” geologic surfaces. A “hard” boundary is one where the interpolation of drill hole data into the block model does not cross geological surfaces, a soft boundary is one where interpolation crosses geological boundaries. The top of Unit 1 (i.e., the ultramafic at the base of Unit 2) is a soft boundary for mineralization estimation as the mineralized domain model crosses from Unit 1 into Unit 2. The base of Unit 1, where it contacts the Virginia Formation, is a hard boundary for estimation and metals values, with virtually all sulfide in the Virginia Formation below as pyrrhotite. No data from Unit 1 is used in estimating grades in the Virginia Formation, or vice versa.

In the up-dip, west half of the deposit there is an arbitrary and diffuse geologic boundary within Unit 1 that vanishes to the east. This is roughly equal to the top of a petrological contamination zone where large quantities of the footwall metasedimentary rocks have been assimilated. This zone is informally called the “front” or “norite zone” by PolyMet geologists. Precious metals values drop off in this zone and pyrrhotite becomes the dominant sulfide. Moderate copper values may persist below this line, but this is essentially a lower physical limit to combined polymetallic grades above the likely project cut-offs.

<table>
<thead>
<tr>
<th>Tonnage</th>
<th>Copper Eqv(1)</th>
<th>Copper</th>
<th>Cu(5)</th>
<th>Ni(5)</th>
<th>Total Precious Metals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>million st</td>
<td>million mt</td>
<td>(%)</td>
<td>m lbs</td>
<td>(%)</td>
</tr>
<tr>
<td>Global Resource (2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td>234.4</td>
<td>212.6</td>
<td>0.73%</td>
<td>3,431</td>
<td>0.26%</td>
</tr>
<tr>
<td>Indicated</td>
<td>654.2</td>
<td>593.5</td>
<td>0.63%</td>
<td>8,202</td>
<td>0.22%</td>
</tr>
<tr>
<td>M + I</td>
<td>888.6</td>
<td>806.1</td>
<td>0.65%</td>
<td>11,633</td>
<td>0.23%</td>
</tr>
<tr>
<td>Inferred</td>
<td>289.6</td>
<td>262.7</td>
<td>0.66%</td>
<td>3,813</td>
<td>0.25%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1,178.20</td>
<td>1,068.80</td>
<td>0.66%</td>
<td>3,813</td>
<td>0.25%</td>
</tr>
<tr>
<td>Mineral Resources (3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td>202.5</td>
<td>183.7</td>
<td>0.79%</td>
<td>3,204</td>
<td>0.29%</td>
</tr>
<tr>
<td>Indicated</td>
<td>491.7</td>
<td>446.1</td>
<td>0.72%</td>
<td>7,052</td>
<td>0.26%</td>
</tr>
<tr>
<td>M + I</td>
<td>694.2</td>
<td>629.8</td>
<td>0.74%</td>
<td>10,255</td>
<td>0.26%</td>
</tr>
<tr>
<td>Inferred</td>
<td>229.7</td>
<td>208.4</td>
<td>0.75%</td>
<td>3,455</td>
<td>0.27%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>923.9</td>
<td>838.1</td>
<td>0.74%</td>
<td>13,701</td>
<td>0.27%</td>
</tr>
<tr>
<td>Reserves</td>
<td>274.7</td>
<td>249.2</td>
<td>0.79%</td>
<td>4,340</td>
<td>0.28%</td>
</tr>
<tr>
<td>Mine Plan (4)</td>
<td>231.1</td>
<td>209.7</td>
<td>0.77%</td>
<td>3,565</td>
<td>0.27%</td>
</tr>
</tbody>
</table>

1. Metals converted to copper based on 2008 DFS Update metal prices
2. 0.1% copper cut-off
3. $7.42/lb net metal value cut-off
4. 20-year mine plan subject to permit applications
5. Base metal percentages rounded off from 2013 Updated resources and reserve data

In the center of the deposit the highest, near surface, Unit 1 grades transition into the middle of the unit, while in the east, mineralization is strong and vertically persistent throughout the unit. The top of the merged Unit 1 and Unit 2 mineralized domain (domain 1) forms a hard boundary that, combined with the bedrock ledge (depth to bedrock) surface, forms the bottom and top estimation boundaries for the upper units (exclusive of the “Magenta Zone”, which is internal to this domain). There is no conclusive relation between specific Unit 1 specific rock type and presence or grade of mineralization except that noritic rocks are generally of lower grade.

Units 2 and 3: These units are treated as one unit in the geologic model, with PolyMet geologists considering them as a single package grading from an ultramafic base to an anorthositic top for modelling purposes. The thickness of the package stays relatively constant, though the thickness of the two individual units varies, primarily due to Unit 2 locally thinning.

While generally barren, Unit 2 has mineralization at its base in the western half of the deposit. These zones may not be strictly equivalent to Unit 1 type mineralization. Copper and nickel values are lower, as is pyrrhotite, but behavior of other metals is inconsistent, with PGE (Pt + Pd +Au) content varying locally.
relative to nearby grades at the top of Unit 1. Above the basal zone of Unit 2 it is usually barren, medium-grained, and homogenous in texture. Average PGE in Unit 2 is slightly above that of Unit 1.

**Unit 3** shows mineralization in the west, in the middle of the unit and near the top. This occurrence is merged into the Magenta Zone.

Units 4 and 5 are also modeled as a geologic package. There is no compelling geologic reason to fully separate these units, the boundary between them being an arbitrary pick based on overall changes in texture from homogenous to heterogeneous, grain size, and plagioclase content, but without a well defined bounding horizon. The top boundary of Unit 5 is the basal ultramafic of Unit 6, which is an unused hard boundary in grade modelling. The bottom boundary of Unit 4 is a discontinuous ultramafic horizon. There are also discontinuous oxide-rich zones along the contact between Units 3 and 4.

Metals and sulfur grades in Unit 4 are proportional to Unit 1, but consistently lower. Unit 4 has few high copper or sulfur assay intervals. There is some near surface mineralization, modelled as a part of the Magenta Zone, described below. Otherwise there is only low grade, discontinuous material at the base.

**Unit 6 and Unit 7:** These units are very similar in nature. Both are homogenous anorthositic troctolites with well defined ultramafic bases. No top for Unit 7 has been seen in drill hole.

Units 3, 4, 5 and 6 host a zone of mineralization, modeled as the Magenta Zone. Unit 6 material was described by Geerts (1994) as the “Magenta Horizon” when originally found in six drill holes. Further drilling has extended these copper rich, sulfur poor zones (of moderate overall grade) into more than fifty drill holes in Units 3, 4, 5, and 6. The zone transitions across the ultramafic base of Unit 6 and into Units 3, 4 and 5, (i.e., does cross the igneous stratigraphy) which is problematic if the emplacement model of these units representing individual pulses of magma is correct. There is no gross evidence for this mineralization being hydrothermal, which could cross boundaries, but would presumably alter large masses of rock.

**Unit 7** has a few good assay intercepts, but no apparent continuity for sulfides.

*Table 5A-5.* Average values for assays by unit after removal of the less than 0.05% copper intervals (drill core samples). Unsampled zones not accounted for here. Data complete through 2006.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Cu %</th>
<th>Ni %</th>
<th>S %</th>
<th>Pt+Pd+Au ppb</th>
<th>Co ppm</th>
<th>Cu+Ni %</th>
<th>Cu/Ni</th>
<th>Cu/S</th>
<th>Total % of unit sampled</th>
<th>Average sample length-feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 1</td>
<td>0.3</td>
<td>0.09</td>
<td>0.83</td>
<td>349</td>
<td>76</td>
<td>0.39</td>
<td>3.35</td>
<td>0.43</td>
<td>90</td>
<td>5.3</td>
</tr>
<tr>
<td>Unit 2</td>
<td>0.2</td>
<td>0.07</td>
<td>0.39</td>
<td>365</td>
<td>73</td>
<td>0.27</td>
<td>2.74</td>
<td>0.61</td>
<td>80</td>
<td>5.6</td>
</tr>
<tr>
<td>Unit 3</td>
<td>0.19</td>
<td>0.05</td>
<td>0.5</td>
<td>286</td>
<td>62</td>
<td>0.25</td>
<td>3.19</td>
<td>0.53</td>
<td>71</td>
<td>7.2</td>
</tr>
<tr>
<td>Unit 4</td>
<td>0.21</td>
<td>0.06</td>
<td>0.58</td>
<td>269</td>
<td>66</td>
<td>0.28</td>
<td>3.40</td>
<td>0.44</td>
<td>51</td>
<td>7.6</td>
</tr>
<tr>
<td>Unit 5</td>
<td>0.27</td>
<td>0.07</td>
<td>0.54</td>
<td>398</td>
<td>65</td>
<td>0.35</td>
<td>3.64</td>
<td>0.54</td>
<td>41</td>
<td>7.8</td>
</tr>
<tr>
<td>Unit 6</td>
<td>0.33</td>
<td>0.08</td>
<td>0.48</td>
<td>532</td>
<td>69</td>
<td>0.41</td>
<td>3.74</td>
<td>0.69</td>
<td>27</td>
<td>7.2</td>
</tr>
<tr>
<td>Unit 7</td>
<td>0.2</td>
<td>0.06</td>
<td>0.32</td>
<td>330</td>
<td>83</td>
<td>0.26</td>
<td>3.60</td>
<td>0.72</td>
<td>11</td>
<td>8.4</td>
</tr>
</tbody>
</table>

Copper, nickel, and sulfur values in Table 5A-5 are calculated after removing samples with less than 0.05% copper. Samples removed are generally those collected for waste characterization purposes, many well outside the expected mining area, and these low values can somewhat obscure the ore chemistry / mineralogy relations in the “ore.” Ratios are calculated on all raw data, not on the copper-nickel-sulfur values shown here.

- No lateral or vertical zonation has been recognized in sulfide or silicate mineral Chemistry;
• Gatehouse (North Mining) did report some geochemical cyclicity in unit 1, but this has not been revisited with the larger data set;
• Poor assay grades in the noritic rocks are related to footwall assimilation and contamination, otherwise there is little connection between grades and specific rock type. About 83% of the igneous rocks at NorthMet are troctolites, 6% anorthositic rocks, 4% ultramafic rocks, and 4% footwall inclusions. The remainder are norites, gabbros, and other;
• Within Unit 1 copper:sulfur ratio tends to be highest at top, then diminishes with depth, following the pattern of PGE’s;
• The upper units have higher copper:sulfur ratios than Unit 1 (i.e., more chalcopyrite rich), but lower overall copper values;
• Ratio of PGE to copper is lowest in Unit 1, but Unit 1 has greatest quantities of both;
• Chalcopyrite is the dominant sulfide in the upper units regardless of total sulfur content;

**Sulfide (Ore) Mineral Proportions**
Various metallurgical test programs have been conducted on NorthMet ores since the 1970’s. Reported sulfide mineral proportions have not been entirely consistent between these tests. Table 5A-6 shows well characterized sulfide mineral proportions for waste rock from studies done by PolyMet in 2006 and results from various previous studies.

Sulfide mineralogy within the NorthMet Deposit has been described in detail through petrographic observations and microprobe analysis. Approximately 95-98% of all sulfide mineralization consists of 4 predominant species, in decreasing order of abundance: chalcopyrite (cp) > pyrrhotite (po) > cubanite (cb) > pentlandite (pn). In general, Po:Cp+Cb ratios increase towards the basal contact or in proximity to sedimentary inclusions. Likewise, Cp:Cb ratios increase with increased distance away from the footwall rocks. In core logging and other work, chalcopyrite is often not distinguished from cubanite.

**Mining**
Mining at NorthMet will begin with contractor clearing and overburden stripping of the pit and stockpile areas. Engineered stockpile bases and liner systems must be in place before mining begins, as does the overall water collection system for treatment and pumping to the tailings basin. Ore and waste production will start in the east pit, with production from the west pit ramping up soon afterwards. Up through about year 11 or 12 production from both pits will be equal until the east pit is mined out. At that point, backfilling of the east pit will begin, with the ultimate goal of constructing a wetland in that pit. The central pit area will be mined last.

Ore will be moved at a rate of 32,000 tons per day. Waste to ore strip ratio will be about 1.46:1. Ore will be moved by truck to the “superpocket” and loaded to 100 ton capacity side dump rail cars by pan feeder. There will be twenty trains per day of 16 cars each.

Ore and waste categorization (“ore control”) will be by assay of core and / or blast holes and careful pit mapping. Waste material will be sorted to stockpiles, and stockpile liners will be built, according to the sulfur and metals content of the waste rock. Over 80% of the waste rock will never produce acid drainage, and about 4% will produce acid drainage within one year. Safe final disposition of this rock will be a permit condition, but as yet the state has not concluded what that condition will be. PolyMet has proposed to place some under capping systems, and to place some underwater.
PART 5B: TECK AMERICAN MESAABA DEPOSIT

By: Mark Severson (portions originally by Tim Jefferson)

BACKGROUND

Previous exploration and development work
The Mesaba deposit was first discovered along the base of the Duluth Complex in 1958 by Bear Creek Mining Company (BMC). Between 1958 and 1960, BMC completed 55 shallow drill holes for 43,000 feet (13,952 meters) on their discovery located 5 miles (8 km) south of Babbitt. BMC renewed drilling activities in 1967-1971 completing 149 additional holes. Drill hole B1-105 intersected substantial amounts of semi massive to massive sulfide mineralization between 1,400 and 1,800 feet (425 and 550 meters) below surface in footwall rock. Subsequent drilling defined a high grade zone appropriately named the Local Boy ore zone after BCM geologist Stuart Behling, the “local boy,” who encouraged BMC to continue drilling this site. Bear Creek defined the overall tonnage and grade for the deposit to be 851 million tons (772 million tonnes) grading 0.46% Cu, 0.12%Ni at 0.25% Cu cut-off.

In late 1973, AMAX Exploration, Inc. agreed to take over BMC’s state and private leases. During the next four years (1974-1978) AMAX continued drilling the deposit (completing 228 drill holes), and evaluated whether an underground operation was feasible (Watowich, 1978). In particular their focus was drawn to the Local Boy ore zone, and following successful permitting, they sank a shaft in 1976-1977. Four drifts totaling 3,800 feet (1,160 meters) were developed and 218 underground holes were completed. This detailed definition resulted in an overall underground resource of 364 million tons (330.2 million tonnes) averaging 0.84% Cu and 0.19% Ni, with a Local Boy-only resource of 5 million tons (4.54 million tonnes) grading 1.89% Cu, 0.36% Ni. Both underground resources were estimated based on a 0.60% Cu cut-off. Due to weakening copper and nickel markets and the inability to produce separate high grade Cu and Ni concentrates, AMAX abandoned their plans to develop the deposit in late 1981. Rhude and Fryberger obtained leases and, along with the NRRI, evaluated the PGE potential of the Local Boy ore zone circa 1990.

Arimetco Inc, picked up the Babbitt deposit leases, renamed it the Mesaba deposit, and evaluated the property circa 1994-1996. They did not complete any drilling but collected two bulk samples for metallurgical test work. Arimetco upgraded the resource estimate to 3,300 million tons (2,993.7 million tonnes) grading 0.46% Cu, 0.12% Ni, cut-off 0.38% Cu (Miller et al, 2002). Arimetco Inc. declared bankruptcy in late 1996.

Present exploration and development work
Teck American Incorporated picked up a package of state and private leases covering the Mesaba deposit in 1997. In 2001, evaluation of the resource included collection of a 5,511 ton (5,000 tonnes) bulk sample. Sulfide concentrates were made from this bulk sample and tested at their Cominco Engineering Services Lab near Vancouver, BC, using their patented CESL hydrometallurgical pressure oxidation process. Definition drilling began in 2007-2008 for a total of 67,430 feet (20,560 meters) in 64 drill holes (Fig. 5B-1). This drilling was concentrated on the western portion of the deposit to complete a 400 foot (120 meter) grid infill program. In addition to this work, a new 4,409 ton (4,000 tonnes) bulk sample was mined in the fall of 2008. Sulfide concentrates from this ore were made at NRRI’s Coleraine Mineral Research Laboratory. The concentrates were shipped to the CESL facilities for a new round of hydrometallurgical tests, including the successful recovery of an intermediate mixed nickel-cobalt hydroxide. Beginning in December, 2012 to the present, Teck has conducted three additional drilling campaigns (Fig. 5B-1). While Teck has not released a new reserve estimate pending completion of
additional definition drilling, they are continuing their evaluation of the deposit on several fronts, including baseline environmental studies, geophysical surveys, and flotation and ore beneficiation/recovery test work at their Applied Research and Technology division at Trail, BC, along with other engineering studies.

Figure 5B-1. Drill hole location map for Mesaba Deposit. Grid north is about 33° west of north.

Re-logging of historic holes at the Mesaba deposit over an 18 year period, in addition to information gained from logging of holes completed in 2007-2008, indicates that the deposit is primarily hosted by a previously unrecognized intrusion within the Duluth Complex (Severson and Hauck, 2008). It is believed that this intrusion, informally named the Bathtub intrusion (BTI) by Tim Jefferson, lies between the Partridge River intrusion (PRI), to the south, and the South Kawishiwi intrusion (SKI) to the north and east. This intrusion is believed to have been fed by a vent in the Grano Fault area on the east side of the Mesaba deposit. The BTI is believed to pre-date the South Kawishiwi intrusion, and is coeval in age to the Partridge River Intrusion. It is further believed, based on drill hole evidence, that igneous units of the PRI and BTI overlap and co-mingle, with the upper units of the PRI overlying the BTI units. Supporting evidence for this new interpretation is based on igneous units that are unique to either the PRI or BTI, and different styles of sulfide mineralization between the two. The following geologic discussion is largely based on the work of Severson and Hauck (2008) but is condensed and summarized.
Figure 5B-2. Preliminary geologic map of the Mesaba deposit, by Tim Jefferson-circa 2009, showing major geologic units of the Bathtub, Partridge River, and South Kawishiwi intrusions. Major structural features associated with the deposit are also shown. Outline of ore deposit and Teck property boundaries are indicated.
GEOLOGIC SETTING OF THE MESABA DEPOSIT

Footwall Rocks
As there is great commonality between the footwall rocks at the NorthMet Deposit and the Mesaba Deposit, they are discussed in the regional geology section.

Structure
As discussed earlier in this guidebook, there are three structural features that are pertinent to understanding the intrusive history of the BTI that include (Fig. 5B-2): 1. an east-west trending paired syncline and anticline in the footwall rocks referred to as the Bathtub Syncline and Local Boy Anticline; 2. a zone referred to as the “Hidden Rise” that separates the PRI and BTI; and 3. a north-trending fault zone, referred to as the Grano Fault, that has been postulated to have been the feeder zone for the BTI and footwall-injected massive sulfides of the Local Boy ore zone.

The paired Local Boy Anticline and Bathtub Syncline have been determined to be related to both pre-Complex/depositional events and later syn-Complex/folding events. Four lines of evidence for these various events include:

1. The top two BIF submembers (A and B) are notably thin or absent along the trough of the syncline due to non-deposition. The BIF A and B were not removed by assimilation as the BIF is always capped by a thin layer of Virginia Formation in the syncline;
2. Recent drilling has found that the iron-formation thickness is also related to depositional features as evidenced by a decrease in thickness of the BIF in the syncline (condensed section) and a rapid formational thickness increase in the adjacent anticline;
3. The VirgSill is thickest along the axis of the anticline and limbs of the syncline, and thins or is absent in the trough of the syncline. This attests to early-Complex structural modification of these earlier sedimentary-related structures – in other words, this modification event provided a more open structural setting along the axis of the anticline for injection of the sill; and
4. Recent drilling has also encountered highly folded and partially melted iron-formation in both the syncline and anticline indicating that the earlier structures were further modified during emplacement of the Complex.

The “Hidden Rise,” as discussed earlier, is a loosely-defined zone wherein scattered hornfels inclusions of footwall Virginia Formation are fairly common. When viewed collectively, the “Hidden Rise” defines an east-west trending “ridge” that is roughly positioned at the contact between the PRI and BTI.

Along the far eastern edge of the Mesaba deposit is the north-trending Grano Fault, so named for the abundant and sometimes voluminous amounts of late granitoid and oxide rich pyroxenitic lenses (OUIs) associated with the fault zone (Severson, 1994). The late intrusive lenses are interpreted to have vertical configurations and were injected along subsidiary fault zones parallel to, and immediately west of, the Grano Fault. The late intrusives cut the troctolitic rocks and thus, demonstrate that the fault was active during and after emplacement of the PRI, BTI and SKI and may represent a rift related transform fault. Other features that are associated with the Grano Fault include:

1. a steep drop in the basal contact (down to the east);
2. the Biwabik Iron Formation, rather than the Virginia Formation, forms the footwall on the east side of the fault;
3. abundant pre-Complex sills are common within the Biwabik Iron Formation along the northernmost trend of the fault at the nearby Serpentine deposit – there the localized increase in the sills outlines the fault trace (Zanko et al., 1994); and
4. a well-defined topographical lineament occurs along the trace of the fault to the south of the Mesaba deposit. Along the eastern edge of Mesaba, a buried valley, defined by contouring the top
of the ledge (Plate IV, Severson et al., 1994b), is also present on the northern extension of the same topographical lineament.

**BATHTUB INTRUSION**

The newly named Bathtub intrusion (BTI) is wholly contained in the central portion of the Mesaba (Babbitt) deposit. The BTI has recently been singled out as a separate intrusion to explain the abrupt change from typical Partridge River intrusion (PRI) stratigraphy, in the southern part of the deposit, to a completely different stratigraphy to the north in the remainder of the deposit. The BTI has been divided into two major units, BT1 and BT4, each of which contain several subunits. These units, in addition to footwall rocks, and structural features, are portrayed in Fig. 5-5.

**BT1 Unit**

The lowermost unit of the BTI is referred to as the BT1 Unit. It is very similar to Unit I of the nearby PRI in that it is heterogeneous-textured at all scales, contains abundant hornfels inclusions near the basal contact, and is the main sulfide-bearing unit at Mesaba. However, there are some important differences between Units I and BT1 that include:

- Augite troctolite is the dominant rock type in the bottom half of BT1 (as is also the case for Unit I) but in many of the cross-sections the entire up-dip portion of BT1 consists of augite troctolite;
- Massive sulfide occurrences are more common near the basal contact in the BT1 than in Unit I (excluding the unique Local Boy ore zone) indicating that sulfide settling may have been a more important mineralization mechanism in the BTI;
- Coarse- to very coarse-grained disseminated sulfides (up to several centimeters across) are exceedingly common in the lowermost portions of BT1; whereas, this same relationship is not so obvious in Unit I – this again implies the importance of a sulfide settling origin, and;
- Ultramafic horizons and patches are very common in portions of the BT1; whereas, similar ultramafic horizons are not as common in Unit I of the PRI.

The BT1 Unit has been further subdivided into several internal subunits that are discussed below.

**BT1-a**

This subunit of the BT1 is a heterogeneous-textured augite troctolite grading to olivine gabbro. The BT1-a subunit is more common in the bottom half of the BT1 Unit and increases up dip (to the north) at the expense of most other subunits of the BT1.

**BT1-c**

At the base of the BT1 there is significant silica contamination of the magma, due to assimilation of the footwall rocks, and noritic rocks (norite to gabbro norite), with common hornfels inclusions, are the dominant rock types. The BT1-c subunit spatially occurs as a rind or coating along the basal contact.

**BT1-uz**

Wherever olivine-rich ultramafic rocks are common over appreciable intervals in the BT1 Unit, this subunit is used to designate ultramafic zones. The ultramafic rocks in these zones range from well-defined layers to zones where irregular ultramafic patches are presumably peppered throughout a troctolitic host rock.

**BT1-at**

This subunit of the BT1 is used to denote areas where anorthositic troctolite is the dominant rock type. The BT1-at zone is generally located at the very top of the BT1 Unit.
BT-sli
A few holes in the western end of the BTI exhibit well-defined modally-bedded rocks consisting of alternating troctolitic and ultramafic rocks. These intervals are designated as BT-sli for the Bathtub Side Layered Interval. The BT-sli subunit occurs about in the center of BT1 unit in close proximity to the “Hidden Rise.” It is difficult to tell if this subunit is a downward continuation of the BTLI or "± Picrite" (as depicted in Fig. 5-5).

BT4 Unit
The uppermost unit of the BTI is referred to as the BT4 Unit. It was originally correlated with Unit IV of the PRI. However, the BT4 Unit is distinctly different from Unit IV in that the BT4 Unit at Mesaba is:

- heterogeneous-textured at all scales and composed of many alternating rock types;
- commonly contains local sulfide-bearing zones; whereas, Unit IV is mostly sulfide-barren – the sulfides in BT4 are generally chalcopyrite-rich in comparison to chalcopyrite/cubanite ores in the underlying BT1 Unit;
- floored by a semi-persistent ultramafic layer termed the "± Picrite" (see discussion below) in the central portion of the Bathtub ore zone; and
- ultramafic layers and modally-bedded zones, termed the Bathtub Layered Interval (BTLI), are common in the central portion of the Bathtub ore zone.

The BT4 Unit as been further subdivided into several internal subunits based on the presence of a dominant rock type. The various subdivisions of the BT4 Unit are briefly discussed below.

BT4-a
This subunit of the BT4 on the cross-sections denotes areas where heterogeneous-textured augite troctolite is the dominant rock type.

BT4-at
This subunit of the BT4 is used to denote areas where anorthositic troctolite is the dominant rock type. Thick zones of BT4-at are common to some cross-sections through the Mesaba deposit and show relatively good correlation and predictability with similar zones in adjacent cross-sections.

"± Picrite"
At the base of BT4 is a semi-persistent olivine-enriched ultramafic horizon referred to as the "± Picrite." It is present in about 70% of the drill holes in the BTI-portion of the Mesaba deposit. The "± Picrite" is generally absent in the up dip direction (to the north) and is variably present to the south in the contact zone between the PRI and BTI. Where present, the "± Picrite" is about 1-15 feet thick, but exceptions are locally present. In some areas, the "± Picrite" consists of several stacked ultramafic horizons, or modal beds, that are interlayered with troctolitic rocks, and thus, the zone represents a collection of several cyclic layers. In other areas of the Mesaba deposit, the "± Picrite" is not always easily singled out as it occurs in close proximity to a downward thickening BTLI with similar ultramafic layers and modal beds. Therefore, in some instances it is difficult to pick the "± Picrite" out of a myriad of ultramafic horizons associated with either the BTLI or BT-sli.

Bathtub Layered Interval (BTLI)
In the vicinity of the Bathtub Syncline and the “Hidden Rise,” ultramafic layers and modal-bedded zones are extremely common within the BT4 Unit. In the eastern half of the Mesaba deposit the BTLI appears to be present in a subhorizontal saucer-shaped morphology. Conversely, in the western half of the deposit, the BTLI is confined to one or two cylinder-shaped zones, albeit with irregular edges, that are positioned in close proximity to the “Hidden Rise.”
Overall, the ultramafic rock types of the BTLI are characterized by alternating assemblages of either/or: melatroctolite (picrite), feldspathic peridotite, peridotite, dunite (minor), olivine-rich troctolite, and troctolite with modal beds of olivine-rich layers. One or more of these rock types may be stacked above the other in no particular order, and the thickness of this assortment may be highly variable between drill holes. The number of individual ultramafic layers present within the BTLI for any particular drill hole varies drastically. In some holes, over 75 individual ultramafic layers and modal beds are intersected, whereas in other holes only a few scattered ultramafic beds are encountered. The range in thickness for each of the individual ultramafic beds also shows considerable variation, ranging from a few inches to over tens of feet thick. Although the BTLI can be correlated as a package of alternating troctolitic and ultramafic layers, each of the individual ultramafic layers cannot be correlated on a hole by hole basis. This situation indicates that the ultramafic layers either: 1) bifurcate/divide into many thin ultramafic layers; 2) pinch out or have very limited spatial extent; 3) some may actually represent dike-like features (filter pressed crescumulates?); or 4) combinations of the above. Further complicating the picture, the inclination of contacts and modal bedding associated with the ultramafic layers are highly variable, ranging from 5°-80° (with localized overturned beds). This variation in inclinations can even be present in a single drill hole. For the most part, the bedding and contact inclinations in the BTLI are steeper higher up in the drill hole and gradually shallow with depth. The shallow to steep angles exhibited by the BTLI may reflect that the ultramafic layers originated via a variety of mechanisms that include: 1) crystal settling to form subhorizontal layers (dominant in the eastern half of the deposit); 2) filter-pressing to form localized dike-like morphologies; 3) slumpage and folding of the beds took place before they were fully crystallized to form highly irregular and overturned beds; 4) compaction differences took place during lithostatic loading of the crystal pile to form steep and irregular beds; 5) cooling and crystallization, or size/density sorting, took place along, and parallel to, the southern wall of the BTI (up against “The Hidden Rise”); or 6) combinations of all of these mechanisms. Whatever their origin, the steep beds displayed by the BTLI in the western half of the Mesaba deposit are inordinately associated with the “Hidden Rise” and the southernmost edge of the BTI.

PARTRIDGE RIVER INTRUSION (PRI) AT MESABA

Many of the igneous rock units that are present at the nearby NorthMet deposit are also present along the southern edge of the Mesaba deposit and are believed to represent units of the Partridge River Intrusion (see previous geologic setting discussion). Additionally, Units IV through VI of the PRI appear to extend northward and overlie the heterogeneous-textured BT4 Unit. This relationship, also depicted in Figure 5B-2, suggests that the BTI was eventually over-ridden/overlain by the upper units of the PRI. The overall timing of emplacement for the PRI versus the BTI is unknown but correlations in the cross-sections crudely suggest the following:

- Units I through III were intruded first along the southern edge of the Mesaba deposit with a vent area located somewhere to the southwest. The “Hidden Rise” generally marks the northern extent of this intrusive activity and originally formed as part of the floor to these units. Unit III may have been intruded as thin lenses across and north of the “Hidden Rise” – this may explain the local presence of Unit III-like inclusions in the BTI.
- Concurrent with or after the above activity, the BT1 Unit was intruded from a vent area located somewhere to the east, possibly from the Grano Fault area. The “Hidden Rise” formed the southern wall of this particular magma chamber.
- The BT4 Unit was intruded into the same magma chamber but was emplaced above the BT1 Unit.
- Concurrent with or after the above activity, Units IV through VII+ of the PRI were intruded from a vent area located somewhere to the southeast. These upper units were emplaced over the BT4 Unit.
MINERALIZATION AT MESABA

The Mesaba deposit is characterized by disseminated sulfide mineralization, which occurs most commonly as accumulations of chalcopyrite, cubanite, pyrrhotite, and pentlandite. Additionally, common occurrences of talnakhite have been noted in close proximity to the “Hidden Rise.” Short intercepts of semi-massive to massive sulfide mineralization are locally encountered in the BT1-c. Sulfur isotope analyses have indicated that the source of the sulfur used in the formation of the sulfides at Mesaba is the Virginia Formation (Ripley, 1986). The model of sulfide deposition entails turbulent injection of units of the BTI wherein immiscible sulfide droplets coalesce within the silicate melts and attract the chalcophile elements (chiefly copper and nickel) through magma mixing. Thus, the most contaminated magma (from assimilation of footwall Virginia formation) hosts basal sulfides that contain excess sulfur relative to intrusive units higher above the footwall. The sulfide content of the rock increases, often dramatically as the footwall is approached. This sulfide content increase is accompanied by the increasing presence of pyrrhotite and a subsequent change in the copper bearing sulfides (cubanite is dominant over chalcopyrite). The disseminated mineralization is generally composed of 1-4% sulfides, but can reach upwards of 8-12% sulfides as the footwall is approached. In addition to the disseminated sulfide and semi-massive to massive sulfide mineralization, sulfides may locally occur as clots up to several cm in diameter, and are seen occasionally as chalcopyrite rich vein fillings indicative of a late sulfide-rich fluid origin.

The most important mineralized zone at Mesaba is the basal zone, starting at the footwall Virginia Formation contact, and ranges between 200 and 400 feet thick (60 and 125 meters thick). Higher up in the intrusive package, often overlapping the BT1-BT4 unit boundary, is a second zone of disseminated sulfide mineralization that is more erratic and discontinuous in nature but contains markedly lower amounts of cubanite and pyrrhotite.

The Mesaba deposit (hosted by the BTI) displays significant differences with the nearby NorthMet deposit (hosted by the PRI). At NorthMet, the ore zone lower in the deposit is more stratiform and near the top of PRI Unit I, while at Mesaba the main mineralized zone starts immediately at the footwall contact zone. As noted in earlier discussions, units of the BTI are more erratic and chaotic than those of the adjoining PRI intrusion. This is also true of the sulfide distribution which is often locally quite chaotic and variable, but overall the basal zone is tied together by adjacent drill holes to define a strongly mineralized ore body of considerable extent. The footprint of the Mesaba deposit is oblong to arcuate in shape, 3,000 by 13,000 feet (925 by 4,000 meters) in approximate dimensions, crops out at the surface on the northern/up-dip side and extends to approximately 1,650 feet (500 meters) below surface in the southern/downdip direction. The strongest basal mineralization is often localized within the Bathtub Syncline. Here, concentration of sulfides by gravitational settling into the footwall depression has likely occurred. Teck American has not released any new reserve/resource estimates, and the reader is referred to historic reserve numbers as reported earlier in this guidebook.

Three geologic cross sections from the western half of the Mesaba deposit depicting composited Cu-Ni grades from historic and recent drilling are displayed below (Figures 5B-3, 5B-4, and 5B-5).
Figure 5B-3. Cross-section 68+00W through the west end of the Mesaba deposit showing grades of significant intervals. Drill holes MB-08-38 from this cross-section will be on display at Teck’s core shack.
Figure 5B-4. Cross-section 44+00W through the west end of the Mesaba deposit showing grades of significant intervals. Drill holes MB-07-15 and MB-08-37 from this cross-section will be on display at Teck’s core shack.
Figure 5B-5. Cross-section 36-100W through the west end of the Mesaba deposit showing grades of significant intervals. Drill hole MB-08-36 from this cross-section will be on display at Teck's core shack.

- 165 ft @ 0.612% Cu, 0.131% Ni
- 190 feet @ 0.521% Cu, 0.103% Ni
- 190 feet @ 0.488% Cu, 0.106% Ni
- 291 ft @ 0.702% Cu, 0.137% Ni
- 148 ft @ 0.710% Cu, 0.137% Ni
- 317 ft @ 0.636% Cu, 0.136% Ni
- 350 ft @ 0.896% Cu, 0.124% Ni
PGE Mineralization at Mesaba

Platinum group element (PGE) mineralization in the BTI at Mesaba occurs to a lesser degree than the other deposits and intrusions. As a general statement, the western side of the Mesaba deposit generally contains very low PGE values, while there are occurrences of anomalous PGE values in the eastern half of the Mesaba deposit. It is postulated that the higher values to the east in the BTI may be related to proximity to the hypothesized vent area of the BTI – the Grano Fault. The southern margin of the Mesaba deposit occurs within the PRI, and thus, contains PGE mineralization similar to the nearby NorthMet deposit. Limited sampling for PGE at the top of Unit I at Mesaba (the equivalent of the Red Horizon at NorthMet – Geerts, 1991; 1994) has encountered Pd as high as 1.3 ppm Pd (Severson and Hauck, 2003).

Generally, the highest PGE values at Mesaba are associated with Cu-rich massive to semi-massive sulfides in the Local Boy ore zone. Analyses from sampled intervals (5-15 feet thick) record values as high as 11.1 ppm Pd, 8.3 ppm Pt, 13.1 ppm Au, and 62 ppm Ag in the sulfide-rich ores (Severson and Barnes, 1991; Hauck and Severson, 2000). The majority of the anomalous PGE values are spatially distributed along the axis of the Local Boy anticline with the highest Cu and PGE values occurring in the west half of Local Boy. The Grano Fault may have served as a feeder zone to the massive sulfides that were injected into the footwall rocks along the Local Boy Anticline as an immiscible sulfide melt. This melt fractionally crystallized in an east-to-west direction and progressively became enriched in PGE towards the west (see discussion below).

Massive Sulfides at the Local Boy Ore Zone of the Mesaba Deposit

Cu-rich massive sulfides near the basal contact of the Complex are locally present at the Mesaba deposit in a small zone referred to as the Local Boy ore zone. In 1976, AMAX Inc. completed a 1,700-foot-deep exploratory shaft (Minnamax shaft), and in 1977, completed four drifts (A, B, C, and D; Figures 5B-6 and 5B-7). Underground Fan drilling (217 holes) was completed in 1978 to further define the massive sulfide distribution. Sulfide minerals include pyrrhotite, pentlandite, chalcopyrite, talnakhite, cubanite, maucherite (nickel arsenide), sphalerite, bornite and late mackinawite, chalcocite, covellite, godlevskite, and native silver (Severson and Barnes, 1991).

Footwall Structures in the Local Boy Ore Zone

Several investigators have recognized that pre-existing structural conditions in the footwall rocks strongly influenced the basal contact of the Duluth Complex (Mancuso and Dolence, 1970; Watowich, 1978; Holst et al., 1986; Martineau, 1989; Severson and Barnes, 1991). Major irregularities in the basal contact are generally related to folds in the underlying country rock indicating that intrusion proceeded more or less along bedding planes in the footwall rocks (Holst et al., 1986). This is readily expressed by a major east-west -trending trough and ridge in the basal contact at Mesaba that coincides exactly with a syncline-anticline that is defined by the top of the Biwabik Iron Formation (BIF). The thickness of preserved Virginia Formation between the Complex and the BIF is variable due to the amount of material assimilated by the Complex.

The Local Boy ore zone is also situated over this anticlinal ridge. The majority of massive sulfide ore zones, hosted mainly by the Virginia Formation (Severson and Barnes, 1991), are broadly coincident with the axis of the anticline. The contoured top of the BIF in the Local Boy area is shown in Figure 5B-6 (left). Similar anticline geometries are also present for the basal contact as shown in Figure 5B-6 (right). All the data indicate that an EW-trending anticline is the major structural feature present within the footwall rocks of the Local Boy area.
Figure 5B-6. Contoured top of the Biwabik Iron Formation at Local Boy (left), and the contoured top of the basal contact between the footwall Virginia Formation and the Partridge River intrusion at Local Boy (right).

The spacing of the contours in Figure 5B-6 suggests that the anticline is asymmetrical with a steeper flank to the immediate south of the anticlinal crest. Also, fault zones in drill core, as well as recognizable fault offsets of correlative units, are most commonly present on the south flank of the anticline. Taken collectively, all these data suggest that additional structural features, in the form of increased faulting and shearing, are more important on the south flank of the anticline in the Local Boy area.

Mineralization Trends in the Massive Sulfide at the Local Boy Ore Zone

The vast majority of massive sulfides at Local Boy are contained within the Paleoproterozoic Virginia Formation. Even though the massive sulfides straddle the basal contact, most of the massive sulfides are associated with either hornfelsed sedimentary inclusions above the contact or with footwall rocks below the contact while the interfingering intrusive rocks are relatively barren of massive sulfides (Severson and Barnes, 1991). This suggests that the massive sulfide ores were not formed in this area by the gravitational settling of sulfides, but rather, the ores formed by injection of an immiscible sulfide melt into structurally prepared areas within the footwall rocks along the Local Boy anticline in a vein-like setting. A similar mechanism is proposed for the Norilsk-Talnakh deposits in Russia.

Even though the basal contact of the Complex with the Virginia Formation is highly undulatory, the massive sulfides exhibit a definite top and bottom. The ore is distributed such that most of it is contained within a zone between 20 feet and 300 feet above the top of the Biwabik Iron Formation. The geologic constraint for the bottom of the ore zone generally corresponds to the top of the VirgSill (a structurally competent unit). The constraints for the upper portion of the ore zone are unknown and may have been obliterated during emplacement of the Complex. Figure 5B-7 is an attempt to show, in a plan view, where massive sulfide zones are present. Also shown in the figure are the different massive sulfide types (ranging from pyrrhotite-dominant to Cu-rich) relative to structural features. The relationships shown in
Figure 5B-7 indicate that: 1) semi-continuous massive sulfide zones are present, mainly to the south of the Kulas Fault; and most important 2) the massive sulfides show a progressive change in an east-to-west direction from Cu-poor massive sulfides to Cu-rich massive sulfides in the vicinity of the Local Boy anticline. These relationships suggest that the injected immiscible sulfide melt underwent fractional crystallization and progressively became more Cu and PGE enriched as it moved through the footwall rocks in an east-to-west direction.

Figure 5B-7. Potential distribution of semi-massive to massive sulfide types (Cu-poor versus Cu-rich) at the Local Boy ore zone (left); and an isopach map of the cumulative thickness of the massive sulfide zones at the Local Boy ore zone (right). Note that the massive sulfides are not present as a continuous blanket, but rather, as one or more stacked disjointed/separated multiple horizons near the basal contact.

A possible feeder vent for the sulfide injection event may have been the Grano Fault, which was repeatedly reactivated during emplacement of the Complex. Other data that indicates that the Grano Fault was a potential feeder vent include: 1) the massive sulfides are more common, and thicker (Figure 5B-7), close to the Grano Fault (feeder) and along the axis of the Local Boy anticline (structurally-prepared site); 2) the VirgSill rarely contains significant amounts of disseminated sulfides – except near the Grano Fault; and 3) the Biwabik Iron Formation rarely contains sulfides – except near the Grano Fault.

In summary, the massive sulfides at the Local Boy ore zone are interpreted to be structurally controlled in that they are situated along the axis of the Local Boy anticline. The massive sulfides are Cu-rich (5-25% Cu) and are almost exclusively hosted by the Virginia Formation. Sulfide textures suggest that the massive sulfides were injected as an immiscible sulfide melt into the footwall rocks. The overall pattern of sulfide types and PGE contents suggest that the sulfides formed via a process of fractional crystallization of an immiscible sulfide melt as it migrated into the footwall rocks. The Grano Fault is inferred to represent the potential feeder zone in this scenario.
PART 5C: TWIN METALS MINNESOTA’S MATUREI DEPOSIT

Dean M. Peterson - Duluth Metals Limited and Kevin D. Boerst – Twin Metals Minnesota

Introduction

Twin Metals Minnesota’s Maturi deposit is the largest and highest-grade classified Cu-Ni-PGE deposit in the 1.1 Ga. Duluth Complex of northeastern Minnesota. The deposit is located near the north end of the South Kawishiwi intrusion (SKI) west-southwest of the junction of the Nickel Lake Macrodike (NLM) and the SKI (Peterson et al., 2006; Peterson and Albers, 2007; Tharlason et al., 2007; Peterson, 2008; Gal, 2008; and White, 2010). The deposit was discovered utilizing a genetic ore deposit model that identified channelized magma flow within the SKI under a large xenolith/ pillar of anorthosite. The model led to exploratory drilling in 2006; deposit discovery and resource estimations in 2007 & 2008; a joint venture with Antofagasta plc in 2010; and significant resource expansion in 2012 (Fig. 5C-1). The company is currently completing a detailed prefeasibility study of the Maturi Deposit with the aim of completing a Mine Plan of Operation (MPO) in 2014.

Resources

The Mineral Resource estimate for the Maturi deposit (completed by AMEC) incorporate assay data from 444 drill holes and 154 wedge off-set holes totalling 1,328,000 feet drilled on the Maturi deposit between 2006 and 2012, in addition to information from 99 legacy holes also in the geologic data base. The November 2012 Resource Estimates for the Maturi (as well as the Birch Lake and Spruce Road deposits) is based on a 0.3% copper cut-off grade to define the resource model. Based on AMEC’s review of metal prices, process recoveries, refining costs and underground mine operating costs likely to apply at the Twin Metals site, the 0.3% copper cut-off grade (highlighted) is considered the base case for the statement of Indicated and Inferred Mineral Resources at this time. The estimates at the cut-off grades higher and lower than the base case are provided to show sensitivity of the cut-off grade (Table 5C-1).

Table 5C-1. November 2012 resource estimate for TMM’s Maturi Deposit.

<table>
<thead>
<tr>
<th>Cu % cut-off</th>
<th>Indicated Mineral Resource¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tons</td>
<td>Million Cu</td>
</tr>
<tr>
<td>0.2</td>
<td>1,137</td>
</tr>
<tr>
<td>0.3</td>
<td>1,065</td>
</tr>
<tr>
<td>0.4</td>
<td>936</td>
</tr>
<tr>
<td>0.5</td>
<td>739</td>
</tr>
<tr>
<td>0.6</td>
<td>538</td>
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</table>

<table>
<thead>
<tr>
<th>Cu % cut-off</th>
<th>Inferred Mineral Resource</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tons</td>
<td>Million Cu</td>
</tr>
<tr>
<td>0.2</td>
<td>782</td>
</tr>
<tr>
<td>0.3</td>
<td>542</td>
</tr>
<tr>
<td>0.4</td>
<td>383</td>
</tr>
<tr>
<td>0.5</td>
<td>256</td>
</tr>
<tr>
<td>0.6</td>
<td>141</td>
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</tbody>
</table>

Note: Tonnages do not include 139 million tons of mineralized rock excluded from the resource in a safety pillar.

¹ CIM Definition Standards (2010) were followed for Mineral Resource estimation and classification.
² TPM is defined as Au + Pt + Pd.
Figure 5C-1. Map of Twin Metals Minnesota Indicated Resources, Inferred Resources, and Exploration Target Areas.

Geology of the Maturi Deposit

The Maturi Deposit is located within the South Kawishiwi Intrusion (SKI), a shallow dipping (~24° east-southeast) sill-like troctolitic intrusion exposed in an 8- x 32-kilometer arcuate band along the northwestern margin of the Duluth Complex. Lithologic units within the Maturi deposit include Mesoproterozoic rocks of the SKI and Anorthositic Series of the Duluth Complex as well as basalt xenoliths of the North Shore Volcanic Group. At Maturi, SKI magmas intruded between hangingwall
anorthositic rocks and footwall granitic rocks of the Neaorchean Giants Range batholith (Fig. 5C-1). Brief descriptions of the lithostratigraphic units within the Maturi Deposit are given in Table 5C-2.

Table 5C-2. Lithostratigraphic units within the Maturi deposit.

<table>
<thead>
<tr>
<th>Duluth Complex and related rocks (1.1 Ga.)</th>
<th>SKI</th>
<th>Giants Range Batholith (2.68 Ga.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anorthositic troctolite to troctolite (ATA Series) - Medium to coarse-grained, homogeneous, well-foliated and locally layered anorthositic troctolite, troctolite, and ophitic troctolitic rocks. In the field, this unit is commonly referred to as the “sea of troctolite”.</td>
<td>Augite-bearing troctolite (Main AGT) - Homogenous, coarse-grained, subophitic to ophitic, poorly foliated augite troctolite characterized by scattered augite-rich pegmatitic clots and patches. Commonly capped by hanging wall inclusions (HB &amp; Ai) and interpreted to be the solidified basaltic liquid that carried the BMZ crystals and sulfides.</td>
<td>Porphyritic quartz monzonite (GRB) - Pink, coarse-grained, hornblende-phyric, porphyritic quartz monzonite with large (1-2 cm) orthoclase phenocrysts. Also contains irregular zones of aplite, lamprophyre, and supracrustal xenoliths. Strongly recrystallized and partially melted locally adjacent to the contact with the SKI.</td>
</tr>
<tr>
<td></td>
<td>Sulfide-bearing troctolite (BMZ) - Heterogeneous, sulfide-bearing, vari-textured troctolite, augite troctolite, anorthositic troctolite, and olivine gabbro with 0.5 - 5% disseminated chalcopyrite, cubanite, talnakhite, pentlandite and pyrrhotite.</td>
<td>Anorthosite (An-Series &amp; Ai) - Undifferentiated Anorthositic Series inclusions. Includes well-foliated very coarse-grained anorthosite, troctolitic-anorthosite, poikilitic troctolitic anorthosite, gabbroic anorthosite, gabbro, and locally troctolite. Inclusions range from a few cm’s to elongate bodies measured in km’s.</td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td>Early modeling of the Maturi Deposit was limited due to wider-spaced drill holes across the deposit area, though Severson (1994) did a remarkable job in defining the igneous stratigraphy of the SKI along a 19 mile strike length. Severson recognized the fact that the rocks below the lower pegmatite (PEG) unit typically contained sulfides and that rocks above the PEG unit were a monotonous sequence of sulfide-barren anorthositic troctolite to troctolite (AT/T), and augite-troctolite (Main AGT).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Two detailed geologic cross sections through the Maturi Deposit are presented in Figure 5C-2. These sections display the continuity of the basal mineralization as well as the differences in the hangingwall stratigraphy from west to east through the deposit. In the east, the deposit is located under an extremely thick (&gt;1,000m) megaxenolith of Anorthosite Series rocks, and in essence the basal SKI can be viewed as a thin sill-like body. To the west, the anorthosite xenolith ends and the immediate hangingwall rocks to the deposit are sulfide-barren troctolites of the Main AGT unit. We interpret that the Main AGT as the solidified troctolite melt that carried the crystals and sulfide droplets of the magmatic slurry.</td>
</tr>
</tbody>
</table>
In 2008, geologists from Duluth Metals came to the realization that the initial basaltic composition SKI magmas that ultimately solidified to create the Maturi deposit intruded as sulfide-bearing, crystal-laden (olivine and plagioclase crystals), magmatic slurries. Based on this new interpretation, the company reinterpreted Severson’s (1994) regional basal stratigraphy (units U3, BH, BAN) of the SKI (Fig. 5C-3).
Maturi into the Basal Mineralized Zone, or BMZ. The company believes that the geometry of the system (sill-like sub-horizontal intrusion) and the inherent crystallinity of the basaltic melts (phenocrysts of plagioclase and olivine) led to crystal sorting and melting of the footwall granitic rocks to create the heterogeneous lithologies and textures of the BMZ.

Final Stratigraphic Order

Anorthosite Series Rocks (1.1 Ga.)

South Kawishiwi Intrusion (1.1 Ga.)

Giants Range Batholith (2.7 Ga.)

Porphyrptic Quartz Monzonite

Maturi Ore Deposit Model

In 2009, Duluth Metals’ geologic staff conceptualized an integrated ore deposit model for Maturi utilizing advanced geological modeling and analysis of drill hole data (The first 155 MEX-Series holes) to identify and characterize higher grade zones of copper, nickel, cobalt, platinum, palladium and gold within the deposit. This modeling characterized the geochemistry and spatial zonation of four distinct types of Cu-Ni-PGE mineralization within the deposit. The four distinct types of mineralization are briefly described below and are presented graphically in Figure 5C-4.

1) PGE-rich disseminated mineralization on the Eastern side of the Nokomis Property.
Large coherent zone of significantly higher grade PGE mineralization is the result of constriction of the magma channelization beneath a large block of older Anorthositic Series rocks.

2) Ni-Co enriched semi-massive sulfides at, or immediately below the base of the magma channel.
This mineralization is believed to have formed by continuous flushing of hot magma through basal magma channels within the deposit. The concentrated heat melted footwall granitoids, which were incorporated into the magma and induced additional sulfide immiscibility beneath the crystal slurry. These new sulfides scrubbed the melt of nickel and cobalt and settled to the bottom of the system.

3) Cu-PGE enriched disseminated mineralization deep in the footwall below the magma channel.
The concentrated heat beneath basal magma channels thermally metamorphosed, and partially melted footwall granitoids. These reactions resulted in volume loss in the footwall and the footwall infiltration and fractionation of accumulated sulfides magma channel sulfides.
4) **Cu-PGE enriched disseminated mineralization at the top of the mineralized zone (Top-Loaded).**

To the sides of the magma channelway, the sulfide-bearing crystal-liquid slurry was intruded as batches of magma out and to the sides of the channel. Since these highly crystalline magmas are distal to the very hot main magma channel, they solidified quickly into sulfide-bearing troctolite. Once the silicates (olivine+plagioclase) are solid, buoyant fractionated sulfide (Cu-PGE) liquid and magmatic waters moved upwards through the solidifying crystal pile and precipitated Cu-PGE sulfide and hydrous silicate minerals beneath the overlying crystal-poor, liquid silicate magma.

![Diagram of the ore deposit model for the Maturi deposit, circa 2009.](image)

**Figure 5C-4.** The integrated ore deposit model for the Maturi deposit, circa 2009.

In 2012, the geology of the mineralized portions (the BMZ) of the Maturi deposit were reevaluated by the geologic staffs of Duluth Metals, Twin Metals, and geologists from AMEC utilizing a significant volume of new, high-quality geochemical and geological data during the completion of an updated mineral resource classification by the consulting firm AMEC.

Mineralization in both the BMZ and footwall at Maturi were reclassified based on patterns in the physical distribution of mineralization as projected on down-hole plots. Sulfide mineralization is characterized by several distinct patterns, including (1) very low grade mineralized intervals showing low variability (Stage 1), (2) moderate grade mineralized intervals showing low variability (Stage 2), and 3) higher grade mineralized intervals showing higher variability and commonly bounded by low grade selvages (Stage 3) (Fig. 5C-5). Significantly, the contacts between different mineralized intervals are typically quite abrupt. A single hole might contain one or several distinct mineralized intervals within the BMZ, including higher grade intervals with the highest grade occurring at the top, middle, or bottom of the section. Based on these criteria, four intrusive subunits, characterized by common grade profiles, were defined in the BMZ. In addition, two distinct suites of mineralization were identified in the footwall rocks, including...
Ni-Co enriched semi-massive to massive sulfide zones and disseminated Cu-PGE enriched zones deep in the footwall granitoids.

The classifications derived from this exercise were validated by multivariate statistical analysis of multi-element geochemical data, including principal component analysis (Fig. 5C-6) and factor analysis. This investigation revealed a significant correlation of multi-element geochemistry to mineralization within the BMZ as well as several possible subdivisions of the BMZ based on both the physical distribution patterns of mineralization and the geochemistry of the host rocks. The Maturi subunits so defined and validated were determined to occur in a consistent stratigraphic order, and are correlative across the deposit.

**Figure 5C-5.** Revised igneous stratigraphy of the BMZ and adjacent rocks within the Maturi deposit.

**Figure 5C-6.** Multi-element principal component analysis plot of MEX-Series drill hole geochemical data.
Typical geochemical plots of Maturi drill holes are presented in Figure 5C-7 and display several of the patterns that were originally identified in the development of the revised geological model of the Maturi deposit. As well, an idealized intrusive sequence model for the SKI in the Maturi deposit area is given in Figure 5C-8 and a NW to SE cross section of the modeled units of the BMZ is presented in Figure 5C-9.

**Figure 5C-7.** Downhole geochemical plots of typical drill holes within the Maturi deposit.
Figure 5C-8. Idealized intrusive sequence model of the SKI in the Maturi deposit area.

Figure 5C-9. Northwest (left) to Southeast (right) cross section through the Maturi deposit depicting the recently modeled geological units of the BMZ.
Detailed descriptions of the seven units modeled for the Maturi deposit is well beyond the scope of this field trip guidebook. However, brief descriptions are provided in Table 5C-3 below and geochemical plots of copper, nickel, and precious metals are given in Figure 5C-10.

Table 5C-3. Interpreted lithostratigraphic-chemostratigraphic units within and adjacent to the BMZ within the Maturi deposit.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>UH</td>
<td>Discontinuous, barren to low-grade, highly variable troctolite</td>
</tr>
<tr>
<td>Stage 3</td>
<td>Continuous, higher-grade, PGE-enriched, heterolithic troctolite and mela-troctolite</td>
</tr>
<tr>
<td>Stage 2</td>
<td>Continuous, moderate-grade, heterolithic, oxide-bearing, augite-troctolite to troctolite</td>
</tr>
<tr>
<td>Stage 1</td>
<td>Discontinuous, barren to very low-grade, homogeneous troctolite, gabbro, and/or norite</td>
</tr>
<tr>
<td>G-N</td>
<td>Irregular, locally high-grade, Ni- and Co-enriched semimassive to massive sulfide pods and veins at or immediately below the basal SKI contact.</td>
</tr>
<tr>
<td>G-M</td>
<td>Discontinuous, low to moderate-grade, disseminated Cu and PGE enriched mineralization.</td>
</tr>
<tr>
<td>G-B</td>
<td>Continuous, barren granitoid footwall rocks</td>
</tr>
</tbody>
</table>

Figure 5C-10. Geochemical boxplots of composited drill hole geochemistry for units within and adjacent to the BMZ within the Maturi deposit.
One of the most important outcomes of the reinterpretation of the geology and mineralization within the Maturi deposit has been the identification of the higher-grade Stage 3 (S3) intrusive unit of the SKI (Table 5C-4). S3 has the highest grade and is the most widely distributed of the four BMZ units (Fig. 5C-11). Cu, Ni, and PGEs and are all significantly elevated in S3 relative to the other BMZ units and the mineralized GRB. Stage 2 (S2) mineralization is overall much lower grade than S3, but locally S2 is well mineralized, and will likely contribute significantly to the deposit economics. Mineralization in the GRB is overall low grade and discontinuous. However, local zones of the unit G-N (where Cu and especially Ni locally occur as massive and semi-massive sulfides) are very high grade and may contribute to the resource.

The current lithostratigraphic model of the Maturi deposit effectively discriminates between higher- and lower-grade mineralization and provides a realistic geological model. The new data allowed correlation of units from hole-to-hole and section-to-section resulting in a very robust geologic model upon which to build mine plans and further our understanding of the magmatic processes that occurred to generate TMM’s Maturi Deposit.

Table 5C-4. November 2012 resource estimate for the Stage 3 unit within TMM’s Maturi Deposit.

| Cu %  | Indicated Mineral Resource 1 |  |  |  |  |  |  |  |  |  |
|-------|-----------------------------|---|---|---|---|---|---|---|---|
| cut-off | Million Cu Ni Pt Pd Au TPM 2 |   |   |   |   |   |   |   |   |
| 0.2   | 643 | 0.68 | 0.22 | 0.20 | 0.45 | 0.11 | 0.75 |   |   |
| 0.3   | 643 | 0.68 | 0.22 | 0.20 | 0.45 | 0.11 | 0.75 |   |   |
| 0.4   | 641 | 0.68 | 0.22 | 0.20 | 0.45 | 0.11 | 0.75 |   |   |
| 0.5   | 622 | 0.69 | 0.22 | 0.20 | 0.45 | 0.11 | 0.76 |   |   |
| 0.6   | 500 | 0.72 | 0.23 | 0.21 | 0.47 | 0.11 | 0.78 |   |   |

| Cu %  | Inferred Mineral Resource   |  |  |  |  |  |  |  |  |  |
|-------|-----------------------------|---|---|---|---|---|---|---|---|
| cut-off | Million Cu Ni Pt Pd Au TPM |   |   |   |   |   |   |   |   |
| 0.2   | 234 | 0.62 | 0.20 | 0.21 | 0.46 | 0.10 | 0.77 |   |   |
| 0.3   | 232 | 0.62 | 0.20 | 0.21 | 0.47 | 0.10 | 0.78 |   |   |
| 0.4   | 225 | 0.63 | 0.20 | 0.21 | 0.47 | 0.10 | 0.78 |   |   |
| 0.5   | 198 | 0.65 | 0.21 | 0.22 | 0.50 | 0.11 | 0.82 |   |   |
| 0.6   | 129 | 0.70 | 0.22 | 0.25 | 0.55 | 0.12 | 0.92 |   |   |

Note: Tonnages do not include 139 million tons of mineralized rock excluded from the resource in a safety pillar.

1 CIM Definition Standards (2010) were followed for Mineral Resource estimation and classification.

2 TPM is defined as Au + Pt + Pd.
Figure 5C-11. Plan views of Stage 3 Cu, Ni, and TPM grades from the TMM Maturi deposit block model.
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FIELD TRIP 6

Geology and Pd Mineralization

at the Lac des Iles Mine, Northwest Ontario

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Regional Setting of the Lac des Iles Mine

The Lac des Iles Mine area is underlain by mafic to ultramafic rocks of the Neoarchean Lac des Iles Intrusive Complex (LDI-IC). The LDI-IC is part of the Lac des Iles Suite, whose mafic intrusive rocks generally range in age between 2686 Ma and 2699 Ma (cf. Stone 2010). These rocks have intruded a variety of ca. 2.9 Ga to 2.7 Ga, metamorphosed granitoid rocks and supracrustal greenstone belt rocks of the Wabigoon Subprovince of the Superior Province (Fig. 6.1). The LDI-IC lies immediately north of the boundary between the volcano-plutonic Wabigoon and metasedimentary Quetico subprovinces. The LDI-IC is the largest of a series of mafic and ultramafic intrusions that occur along the boundary and which collectively define a 30 km diameter circular pattern (Fig. 6.2).

There are three broad, temporally diverse settings for Archean PGE mineralization west of Lake Nipigon (cf. Smyk et al. 2002):

1. Pre-tectonic mafic to ultramafic subvolcanic(?) intrusions intimately associated and coeval with greenstone belts of various ages in the Wabigoon Subprovince;
2. Mafic intrusive rocks occurring within syn- to post-tectonic, diorite-monzodiorite-monzonite suites with sanukitoid affinity within the Wabigoon and Quetico subprovinces (e.g., Shelby Lake batholith, Stone et al. 2003; Roaring River Complex, Schnieders et al. 2002).
3. Post-tectonic, mafic to ultramafic intrusions related to late plutonism in the Wabigoon Subprovince, hosted by gneissic tonalite-granodiorite (e.g., Lac des Iles suite).

Pre-tectonic, deformed mafic to ultramafic intrusions and/or coeval komatiitic metavolcanic rocks within greenstone belt assemblages may host copper-nickel-PGE mineralization. This broad classification is equivalent to the “komatiitic-associated” and “intrusions comagmatic with volcanic rocks” settings for copper-nickel-PGE + chromium mineralization described by Fyon et al. (1992). Such deposits are characterized by remobilized, deformed and annealed, net-textured to massive sulphides. Examples include the past-producing Shebandowan Mine in the Shebandowan greenstone belt, west of Thunder Bay (8.64 million tonnes mined, grading 1.92% Ni, 0.98% Cu, 2.62 g/t Pt+Pd; Resident Geologist’s Files, Thunder Bay South District, Thunder Bay). In the Obonga Lake belt, the Core Zone gabbro (2733 ± 7 Ma; Tomlinson et al. 1999) and the Puddy Lake serpentinite both may contain indications of such mineralization. Lavigne et al. (1991) reported metal contents from the Puddy Lake serpentinite up to 5.02% Cu, 2.1% Ni, 415 ppb Au, 1500 ppb Pt and 3750 ppb Pd; cobalt values of 0.07% were reported from drilling in the 1960’s (Lavigne et al. 1992).
Figure 6.1: Regional setting of the Lac des Iles complex and related ultramafic and mafic intrusions within the Wabigoon Subprovince (from Lavigne and Michaud, 2002).

Figure 6.2: General geology in the Lac des Iles Intrusive Complex area from Lavigne and Michaud (2002)
PGE mineralization is also associated with rocks of the sanukitoid suite (ca. 2688 to 2690 Ma, Davis et al. 1990; Kamo 2004; cf. Stern et al. 1989). The Shelby Lake batholith which consists of hornblende leucogabbro (diorite) to monzodiorite and hornblende granodiorite to granite, contains disseminated sulphide zones in thin units of hornblende gabbro distributed along its northwestern margin (e.g., Turtle Hill and Stocker occurrences). Similar, somewhat larger sulphide occurrences have been described (Stone et al. 2003). At Wakinoo Lake, Towle Lake (e.g., Powder Hill, Stinger and Vande occurrences) and Legris Lake (e.g., Main and Poplar occurrences). Diamond drill holes in hornblende gabbro at Legris Lake (Fig. 6.2) contained 2.04 g/t Pd, 0.41 g/t Pt, 0.71 g/t Au, 0.42% Cu and 0.13% Ni over 9.95 m (News Release, Avalon Ventures Ltd. and Starcore Resources Ltd., November 10, 2000). The Roaring River complex (Stern and Hanson 1991) consists of a variety of plutonic rocks including diorite, monzodiorite, monzonite, quartz monzodiorite and granodiorite, all of sanukitoid affinity; gabbroic and pyroxenitic mega-inclusions occur in these phases. Grab samples of the Mere showing contain up to 1249 ppm Ni, 3159 ppm Cu and 1.1 g/t Pt+Pd+Au; the Leigh (boulder) occurrence returned up to 2067 ppm Ni, 1920 ppm Cu and 1.23 g/t Pt+Pd+Au (Schnieders et al. 2002 and references therein). Disseminated to locally net-textured chalcopyrite, Fe-sulphides, pentlandite and magnetite typically characterize PGE-mineralized zones, which are commonly associated with intrusive contacts, polyphase intrusive breccia, and sheared and hydrothermally altered zones.

Mafic to ultramafic intrusions of the Lac des Iles suite (ca. 2686-2699 Ma; Stone 2010 and references therein; Davis 2003; Kamo 2004) and their associated copper-nickel-PGE mineralization at the North American Palladium Ltd.’s Lac des Iles mine were most recently described by Stone et al. (2003). This suite includes the Buck Lake, Dog River, Taman Lake, Demars Lake, Bullseye and Tib Lake intrusions (Fig. 6.2), as well as the Northern Ultramafic intrusion and Mine Block intrusion at Lac des Iles (Fig. 6.3). These leucogabbro and gabbronorite intrusions (+ anorthosite, peridotite) range from 1 to 10 km in diameter and are considered to represent a continuum of the Quetico suite of mafic to ultramafic intrusions (cf. MacTavish 1999; Pettigrew et al. 2000).

Michaud (1998), Lavigne and Michaud (2002) and Lavigne et al. (2005) provided recent descriptions of the Mine Block intrusion (Fig. 6.4). Platinum group elements are associated with disseminated Cu-Ni-sulphide minerals in the matrix of magmatic breccia, and in vari-textured to pegmatitic gabbroic rocks (which together represent the Breccia Zone), and also in pyroxenite that is part of the High-Grade Zone. PGE also occur with sulphide-poor, vari-textured to pegmatitic gabbro in the Roby and North Roby zones and are locally associated with strong silicate alteration (e.g., Roby Zone and portions of the High-Grade Zone; Lavigne et al. 2005). The Roby Zone is the product of multiple stages of intrusion, alteration and mineralization (Lavigne et al. 2005).
Figure 6.3: Geology of the Northern Ultramafic and Mine Block intrusions of the Lac des Iles Complex (from Lavigne and Michaud, 2002).
Hinchey et al. (2005) put forward a schematic model illustrating a deposit model for the history of mineralization at the southern Roby Zone (Fig 6.5). The textures of the Lac des Iles deposit are similar to those of contact-type PGE deposits, but there are fundamental differences between the two. The Lac des Iles deposit is not localized near the contact between the host intrusion and the country rocks and evidence of the assimilation of the host rocks is lacking. Instead, the mineralization at Lac des Iles has many features in common with layered intrusion-hosted deposits, in which pulses of primitive magma introduced the PGE. Unlike the quiescent magma chambers of most layered deposits, the magmas at Lac des Iles were intruded energetically, forming breccias and magma mingling textures. Magmas formed by a high degree of partial melting in a depleted mantle source (Fig. 5, A1) became enriched in Cu, Pt, and Pd through fractional crystallization of olivine, chromite, and high-temperature PGM (Fig. 5, A2), segregated sulfide melt that had low Cu/Pd ratios along the conduit and the base of the magma chamber (Fig. 5, A3), and solidified as the early leucocratic gabbros. A second episode of partial melting in the mantle source produced another batch of fertile magma. As with the early magma, this magma was enriched in Cu, Pt, and Pd through fractional crystallization (Fig. 5, A2). This magma incorporated the earlier sulfide melt and intruded forcefully into the partially crystallized leucocratic rocks (Fig. 5, B1), causing brecciation and magma mingling, and solidified as fertile melanocratic gabbro. Aqueous fluids that separated from the melanocratic magma percolated
through the cumulates, partially dissolving Pd and concentrating it in the High Grade ore zone adjacent to barren East Gabbro (Fig. 5, B2).

Figure 6.5. Schematic mineralization model for the Lac des Iles Mine (Hinchey et al. 2005)
History of Exploration and Mining

The Lac des Iles area was initially mapped by Jolliffe (1934) and later by Pye (1968), Watkinson and Dunning (1979), Sutcliffe and Sweeny (1985, 1986), Sweeney and Edgar (1987), Stone et al. (2003). The regional geology has been summarized by Stone (2010). Economic interest in the area was sparked by the ground-truthed aeromagnetic anomalies. Significant palladium mineralization was first discovered in the Roby Zone in 1963 by a prospecting syndicate. Various exploration programs were undertaken over the next 25 years by a number of companies, including Gunnex Ltd., Anaconda Ltd., Texas Gulf Sulphur Co. Inc., and Boston Bay Mines Ltd. In 1990, Madeleine Mines Ltd., a precursor to North American Palladium Limited (NAPL), developed the property. After intermittent production and continuing capital expenditures, commercial open pit production of the Roby Zone (Fig. 6.4) was achieved in December 1993. NAPL was formed through corporate reorganization.

In 2000, an expansion program began and a new mill was commissioned in the second quarter of 2001 to achieve its rated 15 000 t per day throughput in August 2002. From 1999 to 2001, an extensive drilling campaign identified mineralization at depth, below the ultimate pit bottom. The drilling identified 2 zones with potential for underground mining: the Roby Underground Zone and the Offset Zone (Fig. 6.4).

On July 31, 2003, a positive pre-feasibility study for underground mining of the Roby Underground Zone (down-dip extension of the open pit Main Zone; Fig. 6.4) was completed, followed by a feasibility study for underground mining in 2004. Underground development on the Roby Underground Zone started in 2004, with the ramp developed and the zone accessed in late 2005. Development muck was delivered to the concentrator in December 2005 and underground commercial production began in March 2006. The Offset Zone, discovered in 2000, was historically subdivided into the Offset High Grade Zone and the adjacent Roby Footwall Zone.

The Offset Zone is the fault-offset, down-dip extension of the Roby Underground Zone that was mined below the Roby open pit until October 2008. A number of surface and underground drilling programs have targeted the Offset Zone since 2001.

In 2008, a surface drilling program focused on exploring targets on the Mine Block Intrusion and on the Southeast Breccia Zone, situated adjacent to the southeastern corner of the open pit (Fig. 6.4).

The Cowboy Zone was discovered in June 2009 during infill drilling of the Offset Zone to support a pre-feasibility study (news release, NAPL, June 25, 2009). It is located 30 to 50 m down-section to the west of the Offset Zone and extends for up to 250 m along strike and 350 m down-dip. It remains open in all directions. Similar to the Offset Zone, the Cowboy Zone appears to consist of several mineralized subzones. Intersections include 5.10 g/t Pd over 4 m, 3.88 g/t Pd over 4 m, and 4.46 g/t Pd over 5 m.

Open pit mining of the Roby Zone began in 1993. The open pit was operated by conventional truck and shovel mining, with low- and high-grade material stockpiled near the on-site concentrator. In May 2004, LDI collared a portal in the northwest wall of the pit and ramped down to access the Roby Underground Zone that continues down-dip from the Roby Zone hanging wall below the pit. LDI began processing development muck from the Roby Underground Zone in December 2005. The ramp was extended around the pit to the north and the
new portal was opened in the east wall in 2006. The Roby Underground Zone reached commercial production at 2000 t per day in April 2006. Operations were suspended in October, 2008 due to the global economic downturn and depressed metal prices. Palladium production at Lac des Iles Mine resumed in April 2010. Since production began in 1993 and through 2008 at Lac des Iles Mine, almost 42 Mt of ore have been processed, and approximately 2.3 million ounces of palladium produced (McCombe et al. 2009).

Production figures in the two years after mining resumed in 2010 are shown in Table 6.1. The updated reference (MD&A 2011) does not break up the Ore Mined into Underground & Open Pit (it is combined in Table 6.1); it shows stats separately for both the Ore Mined for Underground and Open Pit. An updated resource and reserve summary as of December 2011 is given in Table 6.2.

Table 6.1: Production figures for Lac des Iles for 2008-2011 (MD&A, 2011)

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>2011</th>
<th>2010</th>
<th>2009</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore Mined</td>
<td>Tonnes</td>
<td>1,830,234</td>
<td>615,926</td>
<td>Mine closed</td>
<td><em>3,676,418</em></td>
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<tr>
<td>Waste Mined – Open Pit</td>
<td>Tonnes</td>
<td></td>
<td></td>
<td></td>
<td>6,964,501</td>
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<tr>
<td>Mill Throughput</td>
<td>Tonnes</td>
<td>1,689,781</td>
<td>649,649</td>
<td>3,722,732</td>
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<td>Pd Head Grade</td>
<td>g/t</td>
<td>3.70</td>
<td>6.06</td>
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<tr>
<td>Pd Recovery</td>
<td>%</td>
<td>78.34</td>
<td>80.80</td>
<td>75.30</td>
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<td>Pd Produced</td>
<td>Oz</td>
<td>146,624</td>
<td>95,057</td>
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<td>Pt Produced</td>
<td>Oz</td>
<td>9,143</td>
<td>4,894</td>
<td>16,311</td>
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<td>Au Produced</td>
<td>Oz</td>
<td>7,267</td>
<td>4,023</td>
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<td>Ni Produced</td>
<td>Lbs</td>
<td>816,037</td>
<td>395,622</td>
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<td>Cu Produced</td>
<td>Lbs</td>
<td>1,596,185</td>
<td>658,013</td>
<td>4,623,278</td>
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</tr>
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</table>

* Added; Ore Mined - Underground + Ore Mined - Open Pit
Table 6.2: Resource figures* for Lac des Iles (MD&A, 2011)

<table>
<thead>
<tr>
<th></th>
<th>Tonnes (000's)</th>
<th>Pd (g/t)</th>
<th>Pt (g/t)</th>
<th>Au (g/t)</th>
<th>Ni (%)</th>
<th>Cu (%)</th>
<th>Pd (000's oz)</th>
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<td><strong>RESERVES</strong></td>
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<tr>
<td>PROVEN - Roby Zone¹,³</td>
<td>283</td>
<td>7.40</td>
<td>0.42</td>
<td>0.36</td>
<td>0.08</td>
<td>0.08</td>
<td>67</td>
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<tr>
<td>PROBABLE - Roby Zone¹,³</td>
<td>637</td>
<td>5.10</td>
<td>0.39</td>
<td>0.33</td>
<td>0.09</td>
<td>0.08</td>
<td>105</td>
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<td>Total Proven &amp; Probable</td>
<td>920</td>
<td>5.81</td>
<td>0.40</td>
<td>0.34</td>
<td>0.08</td>
<td>0.08</td>
<td>172</td>
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<td></td>
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<td></td>
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<tr>
<td>Offset Zone¹,²</td>
<td>2,500</td>
<td>5.62</td>
<td>0.36</td>
<td>0.33</td>
<td>0.12</td>
<td>0.09</td>
<td>452</td>
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<tr>
<td>Open Pit¹,³</td>
<td>3,722</td>
<td>1.99</td>
<td>0.23</td>
<td>0.17</td>
<td>0.07</td>
<td>0.08</td>
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<td>Stockpile¹,³</td>
<td>508</td>
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<td>0.18</td>
<td>0.07</td>
<td>0.05</td>
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<td>Total Measured</td>
<td>6,730</td>
<td>3.36</td>
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<td>0.23</td>
<td>0.09</td>
<td>0.08</td>
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<td>Offset Zone¹,²</td>
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<td>5.24</td>
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<td>0.32</td>
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<td>0.10</td>
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<td>7.62</td>
<td>0.44</td>
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<td>770</td>
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<td>Open Pit¹,³</td>
<td>2,565</td>
<td>2.20</td>
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<td>0.18</td>
<td>0.07</td>
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<td>Total Indicated</td>
<td>31,029</td>
<td>3.40</td>
<td>0.26</td>
<td>0.21</td>
<td>0.09</td>
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<td>3,384</td>
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<tr>
<td>Total Measured &amp; Indicated</td>
<td>37,759</td>
<td>3.39</td>
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<td>0.09</td>
<td>0.06</td>
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<td>Offset Zone¹,²</td>
<td>3,071</td>
<td>4.80</td>
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<td>0.22</td>
<td>0.08</td>
<td>0.07</td>
<td>474</td>
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</table>

* The mineral reserve and resource estimate for the Roby Zone, open pit and and stockpiles were estimated as of June 30, 2010 by Scott Wilson RPA and updated by David Penna, P.Geo., an employee of the Company and a Qualified Person under 43-101 to: (i) to reflect additions to mineral reserves in the Roby Zone as a result of a lower cut-off palladium grade and higher palladium price in the Roby Zone; (ii) depletion from production up to May 31, 2011, and (iii) mineral reserves from the crown pillar (supported by an internal engineering report). The following cut-off grades were used: (i) 1.8 g/t PdEq for the Roby open pit, within an optimized pit shell run below the current pit survey; (ii) 1.9 g/t PdEq for the mine stockpiles; and (iii) 5.8 g/t PdEq for the underground Roby Zone. These cut-off grades were determined under the assumption that production would take place at a rate of 14,000 tpd. Metal price assumptions of US$350/oz palladium, US$1,400/oz platinum, US$850/oz gold, US$6.50/lb nickel, and US$2.00/lb copper were used in the estimation of cut-off grade. A US$/Cdn$ exchange rate of 1.11 was also applied.
Local and Property Geology (from McCombe et al. 2009)

The mine lies in the southern portion of the Lac des Iles Intrusive Complex (LDI-IC) (Fig. 6.3), in a roughly elliptical intrusive package measuring 3 km long by 1.5 km wide, termed the Mine Block Intrusive (MBI; Fig. 6.4). It hosts a number of PGE deposits; the most important of these is the Roby Zone (and its 3 subzones: the North Roby Zone, the High Grade Zone, and the Breccia Zone).

The MBI comprises rocks with a very wide range of textures and mafic and ultramafic compositions, ranging from anorthosite to clinopyroxenite, leucogabbro-norite to melanonorite, and includes magnetite-rich gabbro (Fig. 6.4). Textures include equigranular, fine- to coarse-grained, porphyritic and pegmatitic, varitextured units and heterolithic gabbro breccias. These last 3 textural types are the most common host to PGE mineralization, including the Roby Zone. The MBI consists of 2 lithologically distinct domains. The oval-shaped domain immediately south of Lac des Iles is lithologically complex and contains widespread PGE mineralization, while the domain further to the south is dominated by massive, medium-grained, PGE-barren gabbro-norite (see Figures 2-2 to 2-4). Extensive stripping has disclosed that the interior of the oval-shaped domain has an abundance of monolithic and heterolithic breccia with an average composition of gabbro-norite. Within this area, individual lithological units are not laterally extensive and chaotically distributed. The most laterally continuous unit is a massive, medium-grained gabbro, referred to as East Gabbro (EGAB) (see Figure 2-5). EGAB is adjacent to a varitextured gabbro “rim” to the west and more equigranular gabbronorite (GN) to the east. The varitextured rim is host to the Roby palladium deposit, where heterolithic gabbro breccia (HGABBX) commonly occurs as pipes and pods, and large blocks (~60 m) of varying composition. A pyroxenite unit (PYXT), at the contact between the EGAB and the HGABBX, is host to much of the High Grade Zone.

The principal rock types in the Offset Zone area include the following:

**East Gabbro (EGAB)** – is a well-known gabbro “marker unit” that is characteristically uniform and compositionally homogeneous. EGAB has very minor alteration, with local trace pyrite and epidote. It has no significant associated mineralization, and bounds the Roby Zone to the east. (i.e., hanging wall contact of the Roby Zone).

**Heterolithic Gabbro Breccia (HGABBX)** – the principal host for the Roby Zone, consisting of a melanogabbro to gabbro matrix with variable clast composition, ranging from leucogabbro to pyroxenite. Clast percentage varies commonly from 15 to 60%. This unit comprises most of the economic ore grade material in the current open pit and underground reserves.

**Varitextured Gabbro (VGAB)** – the majority of rock types, excluding EGAB, have a varitextured counterpart. The VGAB varies from leucocratic to pyroxenitic, with grain sizes from fine to very coarse, to pegmatitic. The coarser-grained units form patches and “veinlets” within finer-grained counterparts.

**Gabbro (GAB)** – the most common gabbros in the MBI are medium grained and equigranular, but range from fine to coarse grained and may locally be leucocratic to melanocratic.
Magnetic Gabbro (MTGAB) – medium-grained, equigranular gabbro occurs within the MBI and contains black, fine-grained, interstitial magnetite (typically < 20%); magnetite content ranges from trace amounts to local, narrow layers of 60 to 95% magnetite.

Pyroxenite (PYXT) – a steeply dipping, thin layer situated along the contact between the Heterolithic Gabbro and EGAB; it hosts the highest proportion of the High Grade Zone. This unit is responsible for much of the high PGE grades. Not all pyroxenites locally carry economic PGE grades.

Gabbronorite (GN) – a 20 to 50 m thick, steeply dipping slab located along the northwestern contact of the EGAB; it is also a host unit of the High Grade Zone, although to a lesser degree than the PYXT. The gabbronorite appears to be a gradational extension of the pyroxenite to the northeast of the mine site.

Gabbronorite Breccia (GNBX) – a palladium-mineralized (Twilight Zone) heterolithic breccia, similar to the HGABBX but without pegmatitic phases or varitextured gabbro; it occurs as a roughly cylindrical pod, approximately 150 m in diameter, completely enclosed by the EGAB.

Dikes – late, post-mineralization, mafic dikes vary from small, discrete bodies that occupy space within the modeled mineralized wire frames to large bodies that control the northern termination of the Offset Zone. A dike swarm approximately 30 m wide and trending approximately easterly was mapped at the southern extent of the Roby Zone.

Two major faults have been interpreted to influence the Offset Zone. The Offset Fault structure displaces the High Grade Zone down and approximately 300 m to the west. This fault, easily picked out in diamond-drill core, is often marked by extensive fault gouge, fracturing and alteration of adjacent country rock, and infilling by mafic dikes. The B2 Fault has recently been recognized and interpreted from the underground Offset Zone diamond drilling. It lies approximately 20 to 40 m below and parallel to the westerly dipping Baker Fault and is marked by narrow intersections of fault gouge, fracturing and late mafic dikes.

Mineralized Zones (see Fig. 6.4 for locations)

The Roby Zone is a bulk-mineable, PGE-enriched disseminated sulfide deposit with a minimum north to south length of 950 m, and a width of 815 m, including the Twilight Zone in the southwestern portion of the deposit. The Roby Zone consists of 3 distinct ore types: High Grade Ore (7.6% of volume), North Roby Ore (5.3% of volume), and Breccia Ore (87.1% of volume). The High Grade Ore is the primary ore type mined underground.

High Grade Zone ore is hosted mainly within a portion of a 15 to 25 m thick unit of locally sheared pyroxenite/melanogabbro. A host to high-grade PGE mineralization, it is located in the east-central portion of the Roby Zone, bounded by the barren EGAB hanging wall and HGABBX-hosted Breccia Ore to the west. The High Grade Zone is primarily confined to a 400 m long segment of the pyroxenite, although it does extend northward into the gabbronorite. The High Grade Zone, striking north-northwest to north-northeast, dips almost vertically near surface and flattens to nearly 45° at depth. Below the open pit, this zone is referred to as the Roby Underground Zone. The zone appears to be terminated down dip by a relatively shallow dipping fault, the Offset Fault.
The Offset Zone, a higher grade zone similar to the High Grade Zone, is located below the Offset Fault structure, where it is displaced down and approximately 300 m to the west. The Offset Zone can be split into 3 horizons and has been divided into 3 subzones: the High Grade (HG) Subzone, the Mid (MID) Subzone and the Footwall (FW) Subzone.

High Grade Subzone mineralization is stratabound, along the contact between the EGAB and the mineralized HGABBX. Within the HGABBX, there is a high-grade core typically constrained to an easily recognized ultramafic unit, the pyroxenite. Width varies from 4 to 30 m, with an average of 15 m. Approximately 2% of the zone is occupied by late dikes (dilution). Less than 1% is occupied by shears and faults.

The MID Subzone is proximal to the HG Zone, generally sharing a common boundary in the centre sections and then splitting away near the top and bottom areas. Palladium grades within the MID Subzone can approximate those high grades found within the HG Zone. Apparent widths can vary from 4 to 90 m, with an average of 15 m. Approximately 4% of the zone is occupied by late dikes (dilution). Less than 1% is occupied by shears and faults.

The Footwall Subzone is a stand-alone band of higher grade mineralization that can be defined based on higher grade intersections within the Footwall varitextured gabbro mineralization. This subzone, located approximately 2 to 40 m from the MID Zone, was interpreted based on vertical continuity seen in the drill hole intersections. It is discontinuous and sinuous in plan and has less of a defined areal extent than the other zones. Apparent widths can vary from 4 to 20 m, with an average of 7 m. Approximately 1% of the zone is occupied by late dikes (dilution). Other mineralized zones present within the MBI, as shown in Figure 2-4, are described below:

The Twilight Zone was removed with the mining of the open pit.

The Baker Zone is located approximately 1 km northeast from the Roby and Twilight zones and contains similar rock types and textures. Gabbronorites/norites have been intruded by east-northeast trending, heterolithic melanogabbro breccia and lesser melanogabbro, leucogabbro breccia, varitextured gabbro and late pyroxenite dikes. Surface exploration has exposed the Baker Zone breccias and associated lithologies over a 150 by 55 m area. The heterolithic melanogabbro breccia hosts blebby to disseminated to narrow veinlets of sulphide with sporadic mineralization in the adjacent lithologies. The north-trending, shallowly westerly dipping Baker Fault appears to truncate the Baker Zone mineralization at depth. Extensive surface exploration by NAP occurred mainly from 1998 to 2001 and consisted of prospecting, stripping/trenching (including the main stripped area of approximately 200 by 120 m), channel sampling, geological mapping and ground induced polarization (IP) / resistivity surveys. Sixteen diamond-drill holes in 1998–99 tested the main portion of the Baker Zone over a 250 m strike length and to a maximum depth of 200 m. Subsequent exploration (trenching and diamond drilling) has tested possible strike extensions of the zone and the area below the Baker Fault.

The Moore Zone is a low-grade, presently uneconomic, mineralized zone approximately 500 m south of the current Roby pit with similar lithologies and textures to other MBI breccias. The central area of interest is a small breccia pod measuring approximately 200 m long, varying from approximately 15 to 115 m wide, which occurs within the massive, medium-grained gabbronorite typical of the more southerly domain of the MBI. The main Moore Zone mineralization is located in the eastern portion of the breccia pod and appears to be structurally
controlled (trending ~030°, dipping 70° east), ranging from 5 to 25 m thick. Prospecting, mapping, trenching, sampling and limited diamond drilling of the Moore Zone have indicated limited economic potential.

The Creek Zone is located approximately 2 km northeast of the Roby pit in the northeastern nose of the MBI, near the contact with the north LDI-IC. Surface trenching has exposed the main portion of the Creek Zone in an area 90 m long by 10 to 40 m wide. It is dominated by low-sulfide breccias that have intruded the varitextured gabbro rim of the MBI. The breccias consist of approximately 90% GBNR clasts and only approximately 10% MGAB matrix. Unlike the Roby Zone, mineralization is not dominantly hosted by the breccia matrix but seems to occur within the pegmatitic gabbronite. Prospecting, mapping, trenching, sampling and limited diamond drilling of the Creek Zone have indicated limited mineralized potential.

**Mineralization**

Platinum group element and base metal mineralization at Lac des Iles Mine appears to be dominantly stratabound along the contact between the EGAB and the mineralized HGABBX. Within the HGABBX, there is a high-grade core typically constrained to an easily recognized pyroxenite unit. Visible PGE mineralization is rare and its occurrence is difficult to predict. In general, economic PGE grades are anticipated within gabbroic to pyroxenitic rocks (in close proximity to the marker unit EGAB) that exhibit strong sausseritization of plagioclase feldspars, strong talcose alteration and association with either disseminated or blebby secondary sulfides. Higher PGE grades (mean – 7.89 g/t Pd, maximum – 55.95 g/t Pd) occur in those portions of the pyroxenite that are altered to an assemblage of amphibole (anthophyllite-actinolite-hornblende)-talc-chlorite. The PGE tenor is not proportional to the sulfide content, and samples free of visible sulfide often contain more than 10 g/t Pd. The high-grade mineralization is located primarily within the western, highly altered portion of the pyroxenite, since much of the pyroxenite between the barren EGAB and the High Grade Zone is low grade. The higher grade “High Grade Ore” is not restricted to the pyroxenite as it commonly straddles the pyroxenite/gabbro breccia contact to widths exceeding 250 m.

The majority of platinum-group minerals occur either interstitially to sulfides as cumulus grains or are associated with sulfides at sulfide-silicate boundaries, occurring as discrete mineral inclusions within secondary silicates of altered rocks (Sweeney 1989; Lavigne and Michaud 2001). Palladium and platinum mineralization within the High Grade Zone consists primarily of fine-grained PGE sulfide, braggite and the telluride minerals, merenskyite and kotulskite (Sweeney 1989; Lavigne and Michaud 2001).

The platinum-group minerals at Lac des Iles Mine include the following (Lavigne and Michaud 2001):

- Braggite (Pt,Pd)S
- Isometrieite Pd11(Sb,Te)2As2
- Moncheite PrTe2
- Sperrylite PtAs2
- Stillwaterite Pd8As3
- *Unnamed* Ag4Pd3Te4
- Melonite, gold,
- Kotulskite Pd(Te,Bi)2
- Merenskyite PdTe2
- Palladoarsenide Pd2As
- Stibiopalladinite Pd5Sb2
- Vysotskite PdS
- *Unnamed* Pd5As2
- Pentlandite Pd in solid solution
References


FIELD TRIP 7

The Thunder Bay North Pt-Pd-Cu-Ni Deposit

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Introduction

The Thunder Bay North Project (“TBN”) is located 50 km northeast of the city of Thunder Bay in northwestern Ontario (see Figure 7-1). The project area contains at least 5, possibly as many as 6, coeval intrusions which define the Keweenawan-age Thunder Bay North Intrusive Complex (see Figure 7-2). One of the component intrusions is host to the Thunder Bay North Pt-Pd-Cu-Ni deposit. The TBN Deposit was discovered in December 2006 during drill follow-up to a 2001 mineralized boulder discovery and comprises a NI43-101 compliant resource of 9.8 million tonnes (Mt) indicated at 2.3 grams per tonne (g/t) platinum-equivalent (Pt-Eq) and 0.5 Mt inferred at 2.9 g/t Pt-Eq, for a total of 790,000 Pt-Eq ounces. It is hosted within the sub-horizontal to moderately plunging, chonolithic, mafic/ultramafic Current Lake Intrusion, which is part of the larger TBN Complex.

Figure 7-1: Location and Regional Geology Map
Figure 7-2: The Thunder Bay North Intrusive Complex and its subsidiary sub-complexes.

Discovery

Mineralized, glacially erratic peridotite boulders (see Figures 7-3 and 7-4A) were discovered in 2001 on the west shoreline of Current Lake by geologists Graham Wilson and Gerald Harper. The boulders were large (up to 2 m in diameter), angular in shape, contained up to 10% disseminated sulphides, and assayed up to 9.5 g/t Pt+Pd+Au, 1% Cu, and 0.3% Ni. The pyrrhotite- and chalcopyrite-rich boulders did not exhibit any rusty weathered surfaces. The property was optioned to Pacific Northwest Capital ("PFN") in mid-2001 who subsequently drilled 6 holes from 3 set-ups from the western shoreline of the lake. All 6 of the holes were barren and PFN dropped the option in 2002. Magma Metals Limited ("Magma") of Perth, Western Australia optioned the claims in 2005. Early in 2006 Graham Wilson (now contracted to work for Magma) discovered an extensive field of mineralized peridotite boulders along the eastern shoreline of Current Lake (Figures 7-3 and 7-4B). After flying an airborne magnetic survey Magma drilled their first diamond drill hole under the east shore boulders in December 2006 and intersected 10.5 m of disseminated sulphides grading 1.4 g/t Pt, 1.3 g/t Pd, 0.5% Cu, and 0.3% Ni. Subsequent airborne and ground geophysical surveys, geological mapping, and over 136,000 m of drilling delineated disseminated to locally massive mineralization over a strike-length of 4.85 km within the chonolithic Current Lake Intrusion ("CLI"). The various surveys and a further 50,000 m of drilling also defined 4 other mafic to ultramafic intrusions, 2 of which are mineralized (the Steepledge Lake and Lone Island Lake intrusions). Several closely related outcrops, discovered in 2013, may represent a potential 6th intrusion presently referred to as the 025 Intrusion. Magma Metals and the Thunder Bay North Deposit were acquired by Panoramic Resources Limited ("PAN") of Perth, Western Australia in June of 2012 and the deposit has been added to their project development stream.
Figure 7-3: Quickbird satellite image showing location of west and east shore boulder fields, the deposit discovery hole TBND001 (first hole of the program) and the Current Lake Intrusion (white outline).

Figure 7-4: Mineralized glacial peridotite boulders that lead to the eventual discovery of the Thunder Bay North Deposit. A. West Shore Boulders. B. East Shore Boulders. Note the typical peridotite weathering pattern and colour and the complete lack of rustiness in the boulders which contain 8 to 10% disseminated sulphides.
Geological Setting

The TBN Project area is underlain by both Archean and Proterozoic age rocks (Figure 7-1). The Archean rocks comprise amphibolite-grade, moderately to strongly deformed clastic metasedimentary and granitoid rocks of the Quetico Subprovince (Williams, 1991). The Proterozoic-age rocks are related to the Keweenawan Supergroup within and marginal to the Midcontinent Rift (Cannon et al., 1989; Sutcliffe, 1991; Smyk and Hollings, 2009). The Supergroup formed from 1140 to 1090 Ma as a Large Igneous Province that is now largely located beneath Lake Superior. The Keweenawan-age intrusions in the Thunder Bay region form diabase sills and dykes, layered and composite mafic intrusions (e.g. the Duluth Complex), layered ultramafic intrusions (e.g. the Seagull, Disreali, and Hele intrusions), and minor mafic-ultramafic complexes like the TBN Complex. The CLI has been imprecisely dated at 1120 ± 23 Ma (Smyk and Hollings, 2009). A new age date is in preparation.

Current Lake Intrusion

The Current Lake Intrusion (see Figure 7-5) consists of weakly deformed and non-metamorphosed mafic to ultramafic intrusive rocks emplaced during a protracted, multi-phased intrusive sequence at a high level in the crust (possibly above 2 km depth). The morphology, rock-types, and orientation of the complex change dramatically along strike (Figures 7-5 and 7-6). The CLI in the Current Lake area is a sinuous, sub-horizontal, roughly tubular body ranging from 30 m in diameter up to 50 m wide and 70 m thick. The CLI in the Beaver Lake area is a shallow plunging, sub-tabular body up to 600 m wide and 200 m thick with an irregular floor and wing-like hybrid intrusive sills at the top and bottom of the intrusion. The CLI in the Beaver Lake East area quickly changes from sub-tabular to a deeply incised V (up to 150 m thick) with the overlying hybrids thickening to the southeast to form a body up to 100 m thick. The morphology of the intrusion again changes a short distance west of the 437 Zone into a 250 to 400 m thick, lopolithic, differentiated mafic body (the SEA Intrusion) with a 10 to 30 m thick, moderately south-dipping and southeast-plunging, tabular, locally mineralized ultramafic body at its base. This basal ultramafic body increases in thickness to over 70m with depth southeast of the present limits of the 437 Zone.

The earliest phases of the CLI comprise a collection of variably altered and hematized, pyritized, texturally variable, locally inclusion-rich, locally carbonate ocellae-rich, fine- to medium-grained hybrid intrusive rocks. They consist of quartz-bearing gabbro to quartz leucogabbro (the dominant phase) to quartz diorite (Chaffee et. al, 2012) and are composed of plagioclase, amphibole±quartz, altered pyroxene, ilmenite, magnetite, and serpentine or iddingsite after olivine, and comprise grey and red sub-types of which the grey is the earliest phase. The grey hybrid commonly forms sill-like bodies that intrude flattening, locally sub-vertical structures and that extend laterally away from the main body of the CLI (the hybrid ‘wings’). The red phase is never present at the base of the chonolith or within the sill-like wings. The hybrids are in-turn intruded by multiple phases of fine-grained (1.0 to 1.5 mm diameter) mineralized olivine melagabbronorite (2-pyroxene gabbro) and lherzolite (2 pyroxene peridotite), which form the mineralized portion of the CLI. The olivine melagabbronorite consists of 30-70% variably serpentinised olivine, 10-25% intercumulus plagioclase, 4-15% clinopyroxene and orthopyroxene, and up to 5% cumulus and secondary magnetite. Compared to the olivine melagabbronorite the lherzolite has more olivine, clino- and orthopyroxene, less plagioclase, and usually less serpentine. Overall, the olivine-rich portion of the CLI is well preserved with increased serpentinization and intercumulus plagioclase content towards the contacts.
Figure 7-5: Current Lake Intrusion with diamond drill holes, defined resource, and non-resource mineralization, and various mineralized zone locations.

The CLI in the Current Lake and Bridge zones area is hosted by Archean granodiorite, tonalite, quartz diorite, and locally pegmatitic leucogranite. The granitoid rocks adjacent to the CLI in the Current Lake/Bridge zone area often show evidence of strong hematization and contact metamorphic melting with quartz grains melting and coalescing into characteristic ribbons. The CLI undergoes its first major morphology change in the western Beaver Lake area when it crosses the Quetico Fault into fine-grained, Archean clastic metasedimentary rocks. South of the fault the CLI becomes increasingly thicker, wider, and more tabular in form and the core of the intrusion changes from olivine melagabbrororite to lherzolite with the melagabbrororite only present along the outer margins of the body. All contacts within the olivine-rich portions are gradational over metres and decimetres. Narrow sub-pegmatitic, varitextured (taxitic) leucogabbro, gabbro, and clinopyroxenite zones exist near the upper contact with the overlying hybrid rocks. The contact of the olivine melagabbrororite with the hybrid rocks can be sharp and undulatory or trangressional and gradational over short 2-10 cm intervals with the hybrids usually exhibiting strong hematite alteration. The contact between the olivine melagabbrororite and the footwall Archean metasedimentary rocks is sharp, irregular, and lacks chilled margins. Metasedimentary rocks adjacent to or above the CLI are strongly hornfelsed with the hanging-wall rocks exhibiting strong hydrothermal epidotization, carbonatization, sericitization, and hematite±pyrite alteration for tens of metres above the intrusion. The strongly altered metasedimentary hanging-wall rocks, particularly above
the Beaver Lake portion of the complex, have undergone strong in-situ brecciation, with fragments often exhibiting jig-saw fit. These breccias have locally been intruded by irregular apophyses of chilled grey hybrid. Southeast of Beaver Lake the plunge of the CLI steepens to moderate and, with depth, the hybrid portion of the intrusion increases dramatically in thickness and areal extent eventually forming a strongly magnetic, roughly circular, lopolithic body with a thickness of up to 400 m and a diameter of greater than 1000 m. This portion of the CLI comprises the aeromagnetic Southeast Anomaly and has been named the SEA Intrusion. It is well differentiated from top to bottom and grades from quartz-diorite/quartz monzonite at the top downward through gabbro and then ferrogabbro near the base. The gabbro/ferrogabbro portion of the CLI in the SEA area is in sharp contact with a variably mineralized lherzolite comprising the basal portion of the chonolith. The shape and areal extent of the lherzolite in this area is presently unknown.

**PGE-Cu-Ni Sulfide Mineralization**

The systematic drilling of the CLI has defined several continuously mineralized zones with a drill-defined strike-length of greater than 4.75 km (Figure 7-5). From northwest to southeast the mineralization defined to date comprises the Current Lake; Bridge; Beaver Lake; Cloud; Beaver Lake East; UE North, UE South, and the 437 zones. The boundary between the Current Lake and Bridge zones occurs at the contact (Quetico Fault) between the Quetico granitoid rocks to the north and the Quetico metasedimentary rocks to the south (both the intrusion and associated mineralization are post faulting) and where the conduit changes from a tubular shape north of the fault to a sub-tabular shape south of the fault. The boundary between the Beaver Lake and Beaver Lake East zones is placed where the multiple mineralized tentacles/streams of the Beaver Lake Zone coalesce into the single mineralized stream of the Beaver Lake East Zone. The Cloud, UE North, and UE South zones (not shown) differ from the other defined zones due to their high metal tenor, low-sulphide content, and their occurrence well above the floor of the intrusion. Only the Cloud Zone has been sufficiently defined to be included within the current resource.

The disseminated sulphide mineralization in the Current Lake and Bridge Zones usually occupies most of the conduit with widths of up to 50 m and thicknesses up to 60 m. The distribution of mineralization in the Beaver Lake/Beaver Lake East zones differs from the Current Lake/Bridge zones in that it is primarily localized at or near the base of the intrusion. This basally loaded mineralization varies in thickness from 2 to 30 m, in width from 20 to greater than 50 m, occurs within depressions on the floor of the conduit, and in the Beaver Lake Zone, particularly the western half, forms an interlocking mesh of anastomosing, mineralized basal channels. Mineralization within the poorly defined 437 Zone again fills the thickness of the conduit (10 to 20 m). The high tenor Cloud, UE North, and UE South zones are nebulous in form, vary greatly in width and thickness, consist of very finely disseminated chalcopyrite (usually <2% total sulphides), and generally occur near the top of the intrusion. An interesting point about these zones is that one end of each zone is attached to an existing, lower tenor, mineralized zone near the floor of the conduit where the conduit is narrow and mineralization fills the conduit. As the intrusion thickens this mineralization stays near the upper contact with no apparent setting towards the floor of the intrusion, possibly due to its very finely disseminated nature.

Mineralization throughout the intrusion ranges from a few percent to greater than 25% sulphides and consists of disseminated pyrrhotite, chalcopyrite, pentlandite, pyrite, with minor cubanite and violarite (see Figure 7-7). Individual grains and composite grains range from less than 0.5 to greater than 10 mm in diameter. Nearly 30 platinum-group minerals have been identified, the most common of which are
Figure 7-6: Variations of morphology of the Current Lake Intrusion from northwest to southeast (A through D). Note the scale-changes in the diagrams and the progressively greater depths to the southeast.

sperrylite (PtAs₂), moncheite (PtTe₂), michenerite (PdBiTe), merenskyite (Pd₃Ni₂As₃), maslovite (PtPdTe), kotulskite (PdTe), braggite ([Pt,Pd]S), palladioarsenide (Pd₂As), insizwaite (PtBi₂), and Majakite (PdBiAs) and they generally occur as tiny inclusions in the sulphides. Sulphide veins, up to 3 cm thick, are common within the Current Lake Zone; large composite sulphide blebs (often exhibiting parachute textures) are common throughout; and sulphide fragments (possibly transported) are present locally. Net-textured and massive sulphide intervals are common in the Bridge and western Beaver Lake
zones, but are rare elsewhere. The hybrid phases are devoid of PGE-Cu-Ni mineralization. Sometimes Cu-PGE-rich veins, veinlets, and small pods of sulphide occur within the footwall rocks immediately below the basal contact of the intrusion. This footwall mineralization is minor in nature and usually occurs less than a metre (never more than 3 m) below the basal contact of the CLI.

The dominantly disseminated sulphide mineralization is high grade. Drill hole TBND061 intersected 61.7 m averaging 2.9 g/t Pt, 2.7 g/t Pd, 0.7% Cu, and 0.4% Ni, including 35.5 m of 4.5 g/t Pt, 4.3 g/t Pd, 1.0% Cu, and 0.6% Ni. Net-textured and massive sulphide intersected near the base of the conduit in drill hole BL10-197 was 14.0 m thick averaging 16.2 g/t Pt, 13.9 g/t Pd, 3.5% Cu, and 1.2% Ni, including 2.6 m averaging 52.8 g/t Pt, 41.5 g/t Pd, 3.9 g/t Au, 61.0 g/t Ag, 11.6% Cu, and 3.3% Ni. The tenor of the sulphides in the Current Lake, Bridge, Beaver Lake, Beaver Lake East, and 437 zones is generally consistent between the zones; however, higher tenor mineralization has been found in the Cloud, UE North, and UE South zones. Overall, the average Pt:Pd ratio of the deposit is a very consistent 1.07:1 (except at very high grades) and the Cu:Ni ratio averages 2:1 (except at very high grades). Figure 7-8 is a longitudinal section of the Thunder Bay North Deposit showing modeled mineralization (0.25 g/t Pt shells), plunge, and the upper and lower contacts of the ultramafic portion of the Current Lake Intrusion.

Strong positive correlations of Pd, Cu and Ni to Pt and very limited post-crystallization alteration, other than late deuteric serpentinization of olivine, indicate preservation of an almost pristine magmatic system at TBN with no observed fault offset of the intrusion. Dynamic magmatism would have played a key role in the sulphide mineralization. Assimilation of adjacent country rocks could have introduced additional sulphur to the system; however, no local source of sulphide has been identified. The occurrence of finely disseminated mineralization throughout the conduit in the Current Lake, Bridge, and 437 zones indicates that the sulphides in these three zones were entrained in the host magma. This is also true for the Cloud, UE North, and UE South zones which occur near the top of the thicker portions of the conduit. Conversely in the Beaver Lake and Beaver Lake East zones, sulphides were deposited at the lowest levels of the intrusion within depressions in the floor of the intrusion. One important observation is that the best mineralized zones within the system are always closely associated with significant changes in the morphology of the conduit.

**Figure 7-7:** Range of Mineralization within Current Lake Intrusion from left to right: disseminated (dominant), strongly disseminated (with possible fragments), net-textured, and massive.
Figure 7-8: Longitudinal section of the Thunder Bay North Deposit. Mineralization greater than 0.25 g/t Pt (open pit cut-off grade) is shown in brown. The open pit is the shaded area outlined in black on the upper left of the section. Drill holes are defined by the vertical & sub-vertical black lines extending from the small magenta dots. The Current Lake Zone is greatly foreshortened due to the projection of the figure. View is from the southwest.

Chemistry

Geochemically the Thunder Bay North Intrusive Complex (and its 6 component intrusions) is grouped with the other early mafic-ultramafic MCR intrusions (Seagull, Disraeli, Hele, Eva Kitto, Sunday Lake, Eagle, Tamarack) on the basis of major, trace, and chalcophile elements. Elevated MgO, Ni, and Cr are characteristic of these rocks and are reflected mineralogically with the common presence of olivine and Fe-Ti-Cr spinel. Trace element abundances display an ocean island basalt normalized pattern with some variability in HREE abundances. Analysis of in-house petrochemical data suggests that parental magmas to the intrusive complex contained 8-10\% MgO with olivine and spinel phases on the liquidus. Major and trace element abundances reflect the olivine content of the rocks in the olivine melagabbro-norite and feldspathic lherzolite phases, whereas major and trace elements abundance in the red hybrid rock-type reflect simple two component mixing of a parental magma with local contaminants of granitic and metasedimentary rocks.

Comparison to Other Deposits

Keweenawan-age magmatic mineralization occurs within other deposits of the Lake Superior region. Examples are the disseminated sulphide deposits of the Duluth Complex in Minnesota (Miller et al., 2002) and the Coldwell Complex in Ontario (Barrie et al., 2002), and the Eagle massive sulphide deposit in the
Yellow Dog Peridotite in Michigan (Ware, 2007). Compared to the Duluth and Marathon disseminated deposits, the TBN deposit is smaller, higher grade in Ni and particularly Pt, and hosted within a magma conduit. Compared to the Eagle massive sulphide deposit, the TBN deposit is larger with higher grades of Pt, Pd, lower Cu and Ni, and a lower Ni/Cu ratio.

Globally, the closest analogue to the TBN deposit may be the magmatic conduit-style deposits at Noril’sk-Talnakh, Russia (Naldrett et al., 1996; Arndt et al., 2003). Similarities of the CLI with Noril’sk-Talnakh are: (1) chonolithic shape of the magma conduits; (2) olivine-bearing to olivine-rich host-rocks (picritic dolerite at Noril’sk-Talnakh, olivine melagabbrobronorite to lherzolite at CLI); (3) basalt parental magma composition, although Noril’sk-Talnakh is ~6% MgO and CLI is 8-10% MgO; (4) spatial and genetic relationship with a Large Igneous Province; (5) high metal tenor of the sulphides; (6) presence of varitextured (taxitic) gabbroic rocks; and (7) strong contact metamorphism of the adjacent country rocks. A comparison of the size of the Thunder Bay North Intrusive Complex with respect to other conduit-style deposits is shown in Figure 7-9.

Drill Core Display

The diamond drill core presented consists of the hybrid and feldspatic lherzolite to olivine melagabbrobronorite intersections from drill hole BL10-197 and includes a very high grade, net-textured to massive sulphide intercept occurring within a prominent depression in the floor of the Current Lake Intrusion. The drill log for the hole, with associated assays, is presented within Appendix 1 and a generalized drill cross-section is presented within Appendix 2.

Figure 7-9: Comparison of the Thunder Bay North Intrusive Complex with other conduit-hosting intrusions worldwide (Figure modified after Beresford, 2009).
References


APPENDIX 1 (see following pages)
| From m | To m | Lithology | Code | Rock Description | Magus | Sulphide | Cpy | Po | Py | Pt | Pd | Cu | Ni | Au | Ag | Co | Cr | SG | Pt + Pd (ppm) |
|--------|------|-----------|------|------------------|-------|----------|-----|----|----|----|----|----|----|----|----|----|----|----|----|                |
| 60.60  | 109.80| Siltstone |      |                  | 0.1   | 0.1      |     |    |    |    |    |    |    |    |    |    |    |                |
| 109.80 | 111.15| Fopal     |       |                  |       |          |     |    |    |    |    |    |    |    |    |    |    |                |
| 111.15 | 115.85| Siltstone |      |                  |       |          |     |    |    |    |    |    |    |    |    |    |    |                |
| 115.85 | 117.15| Granodiorite |    |                  |       |          |     |    |    |    |    |    |    |    |    |    |    |                |
| 117.15 | 121.40| Siltstone |      |                  |       |          |     |    |    |    |    |    |    |    |    |    |    |                |

Hole Number: BL10-197

Magma Metals (Canada) Ltd.

Drill Company: George Downing Estate Drilling

Logged: Kyoko Nakano

Start Date: 29/01/2010

End Date: 31/01/2010

Coordinates (NAD 83, Zone 16)

Northing: 5402990.38
Azimuth: 354.6°
Easting: 357950.90
Dip: -89.27°
Elevation: 504.41
Final Depth: 240.00
**Hole Number:** BL10-197

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**Coordinates (NAD 83, Zone 16)**

- **Northing:** 5402390.38
- **Easting:** 357950.90
- **Azimuth:** 354.6°
- **Dip:** -89.27°

**Elevation:** 504.41

**Final Depth:** 2430.00
FIELD TRIP 8

The Marathon Cu-Ni-PGE Deposit in the Coldwell Alkaline Complex

Dave Good, John McBride, Katrina McLean, Ryan Ruthart and Rachel Epstein

Stillwater Canada Inc., Dundas, Ontario L9H 2T5
Introduction

The Coldwell Alkaline Complex is 25 km wide, semi-circular in shape and composed predominantly of internal syenite and nepheline syenite units and an outer rim or marginal zone of complicated tholeiitic and weakly alkaline gabbroic to ultramafic rocks that together form the Eastern Gabbro (Fig. 8.1; Good et al., in preparation). The Geordie Lake gabbro and Coubran Basalts are associated with the Eastern Gabbro but are located near the middle of the complex.

Core on display is from the following three occurrences associated with the Eastern Gabbro, as follows:

1) The Marathon deposit is hosted by the mildly alkaline gabbroic intrusion known as the Two Duck Lake gabbro and contains over 3 million ounces of Pd, Pt and Au and 620 million pounds of copper.
2) The Four Dams Cu-PGE mineralization is hosted by Apatitic clinopyroxenite.
3) The Geordie Lake deposit is hosted within gabbro and troctolite and is associated with an unusual assemblage of skeletal and zoned olivine crystals in close proximity to albite alteration.

Figure 8.1: Location map of the Marathon deposit and Four Dams occurrence near the base of the Eastern Gabbro in the Coldwell Alkaline Complex. The Geordie Lake deposit is hosted by the Geordie Lake Gabbro located in the centre of the Complex.
Marathon Deposit

The Marathon Deposit consists of several large, thick and continuous zones of disseminated sulphide mineralization hosted within the Two Duck Lake gabbro. The mineralized zones occur as shallow dipping sub parallel lenses that follow the basal gabbro contact and are labeled as footwall, main, hanging wall zones and the W Horizon. The Main zone is the thickest and most continuous zone.

The relative proportions of pyrrhotite and chalcopyrite vary significantly across the deposit, but in general, the sulphide assemblage changes gradually up section from the base to the top of mineralized zones. Sulphides at the base of the TDL Gabbro consist predominantly of pyrrhotite and minor chalcopyrite but the relative proportion of chalcopyrite increases up section to nearly 100% chalcopyrite near the top. In the W Horizon, sulphides consist mainly of chalcopyrite and bornite and minor to trace amounts of pentlandite, cobaltite, pyrite and pyrrhotite.

The W Horizon forms a nearly continuous sheet of mineralization that strikes north south for 1.4 km from section 5403125N to section 5404525N and continues down dip for over 650m. The zone is open at depth. It ranges in thickness from 2m (minimum sample width) to 30 m and occurs near the top of the mineralized zones. The zone is difficult to identify in drill core because it commonly contains only trace sulphides, but if sulphides are present, they consist of chalcopyrite and bornite. Continuity of the W Horizon between drill holes is shown by minimum PGM abundances of 1 g/t and by Cu/(Pt+Pd) ratios less than about 3500.

Several very high grade lenses up to 30 m x 200 m in size occur within the W horizon. The highest intersection to date contains 107 g/t PGM+Au, 1.04 g/t Rh and 0.02% Cu over 2 m (hole M07-239), but the best intersection contains 45.2 g/t PGM+Au and 0.49 % Cu over 10m (hole M07-306).

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Figure 8.2: New classification for rocks of the Eastern Gabbro. Mineralized intrusions belong to the Marathon Series and include Oxide melatroctolite, Two Duck Lake gabbro (Marathon deposit) and Apatitic clinopyroxene (Four Dams occurrence).
Figure 8.3: Geology of the Marathon Deposit (Marathon PGM Corp and Stillwater Canada Inc.)

Figure 8.4: Cross section through a portion of the Main Zone, including hole M11-525.
Figure 8.5: Location map of drill holes and respective core samples. Oblique view looking east.

Figure 8.6: Photo of visible PGM in core specimen from 10 m interval with 21 g/t Pd, 9.7 g/t Pt, 1.6 g/t Au and 0.21% Cu in hole M07-304. PGM is 1 cm long and resembles a bright silver thread. Purple mineral is bornite and yellow green mineral is chalcopyrite. PGM identified by Imran Meghji (University of Western Ontario) and photo by K. McLean.

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Marathon Main Zone in Core M11-525

Drill Hole M11-525

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Marathon W Horizon in Cores M07-304 and M07-306

Drill Hole M07-304 and M07-306

Host rock is Two Duck Lake Gabbro

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Four Dams Occurrence in Core B05-13

Figure 8.7: Plan view of the Four Dams mineralization.

Hole B05-13: Interval from 46 to 112 m with 0.41 % Cu and 0.18 ppm Au+Pt+Pd

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Figure 8.8: Section through hole B05-13 (Four Dams occurrence). Evidence for intrusion of crystal slurry accompanied by mechanical sorting

Figure 8.9: Photo of troctolite in mineralized zone with skeletal olivine.
Figure 8.10: Photo of heterogeneous gabbro in mineralized zone with albite and zoned olivine.

**Geordie Lake Deposit in Core G10-16**

Figure 8.11: Plan view of the Geordie Lake Gabbro
Hole G10-16: 57 m interval from 168 to 225 m with 0.46 % Cu, 0.06 g/t Au, 0.05 g/t Pt and 0.83 g/t Pd

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FIELD TRIP 9

Nipigon Reefs Project: A New Look at the PGE-bearing Seagull Mafic-Ultramafic Complex

Graham Wilson and Gerald Harper
Minfocus Exploration Corp, Toronto, Ontario M8V 2E8
Location and Regional Setting

The Seagull complex is a Keweenawan-age mafic-ultramafic intrusion, located some 90-100 km by road north of the city of Thunder Bay in northwestern Ontario. Access is from the Armstrong highway (Hwy. 527), proceeding east on the unpaved Dorion Cut-off Road to north-bound logging access points such as the Manchester, Upper Wolf and Anders Lake roads. From these main arteries, sundry old and often overgrown forestry and drill-access roads are variably accessible by truck, all-terrain vehicle and foot.

The Seagull intrusion is a layered intrusive complex some 85 km² in area, ovoid in plan, ~8-10 km wide and at least 800 m thick from the peneplaned surface down to the basement rocks in the deepest drilled sections. It is part of the Midcontinent Rift magmatic event, interpreted as a failed rifting event dated at ~1100 Ma, manifested in Ontario as an extensive suite of diabase sills in the “Nipigon Embayment”, plus basaltic volcanic rocks preserved further south along Lake Superior, and a small number of mafic-ultramafic intrusions, of which Seagull is the largest found to date in the district (though much smaller than the Coldwell complex to the east, and the Duluth complex in Minnesota, to the southwest).

The area exhibits moderate relief, some 400 m above sea level (200 m above Lake Superior). The region is part of the Canadian boreal forest, in North American climate zone 3, with warm summers and cold winters, dotted with lakes and commonly quite flat except on the borders of mesa-like plateaux topped by Keweenawan diabase sills. Exposure is generally quite limited, and often best on roadside outcrops and hillsides, while lowlands are commonly dotted with black spruce and white cedar swamps, stands of tag alder, and beaver-dammed ponds and lakes. Road construction and other activities related to the logging industry have created many of the outcrops in areas of otherwise minimal exposure. Much of the area is subject to decadal cycles of forestry, with extensive clear-cut areas which encourage growth of shrub and wildflower species that are limited to absent in more mature forest. Some ecological disruption resulted from a spruce budworm infestation and consequent spraying program in the 1980s.

History of Exploration

We will limit ourselves to a brief discussion of selected events and features: see Heggie (2013: this conference) for a more detailed overview of the Seagull complex.

Property-scale exploration, since the early recognition of platiniferous black sand deposits, has focused on a magnetic high in the north-centre of the complex, referred to as the “Leckie stock”, centred southeast of Leckie Lake. A spatial database compiled for Minfocus by G. Harper currently includes some 86 diamond drill holes (excluding auger holes, plus drilling by Magma Metals and its successor company Panoramic Resources, in the south-central area of the complex in 2012-2013). Relatively few holes have tested targets beyond the Leckie stock, exploring a variety of structural, geophysical and geochemical features. It is probably fair to say that the bulk of drilling to date has been based upon geophysical models, with some interest in inferred regional structures, particularly the NNW-SSE trend parallel to the length of Black Sturgeon Lake (located to the northeast, south of Lake Nipigon). Other data for targeting has come from distribution of heavy minerals and from lake sediment geochemistry, though the generally thin (<5 metres) but pervasive glacial till cover, and the rather cryptic, low-sulphide style of PGE mineralization limit the possibility of generating targets from geological outcrop.

Interest in the mineral potential of the Seagull complex began in a fitful manner in the late 1980s and early 1990s. The current, ongoing interest in the intrusion dates to the 1997 staking of claims by prospector R.J. Fairservice of Kenora, who optioned his property to Avalon Ventures Limited. The claims included areas of black sand, formed by the in situ weathering of a micaceous peridotite, which assayed as high as 7.66 ppm.
Pt+Pd. Avalon undertook a program of trenching and pitting, ground magnetometry on a cut grid and petrography, and followed up with 12 auger holes and 8 diamond drill holes (Osmani and Rees, 1998a,b). The work defined the Leckie stock, which it was judged might postdate the bulk of the Seagull complex to the south (Osmani and Rees, 1998a), and made a start at defining the igneous stratigraphy of the complex, including a diabase / gabbro sill with a chilled upper margin, which cuts the mafic-ultramafic sequence and has been encountered in subsequent drill programs. Avalon’s good work continued (Pettigrew, 2002) and led to recognition of three styles of mineralization: the surficial black sands, reef-style low-sulphide mineralization within the layered sequence, and basal sulphide accumulations at the footwall, against either Archean gneiss, migmatite and granitoid rocks of the Quetico subprovince, or calcareous to clastic sediments of the Mesoproterozoic Sibley Group.

The authors began prospecting in the region in 1993 at Onion Lake, west of Current Lake, and gradually worked their way eastward. They set up a private company, Minfocus, in 1994, though this was largely inactive until it was decided to take the company public, a goal achieved in January 2012. Minfocus Exploration Corp. came to the Seagull complex first by staking claims east and southeast of the intrusion as early as 2009, in the Springlet Lake area. Certain of the local lakes display elevated lake-water Pt and Pd values. Diamond drilling was undertaken in 2010 (12 holes) and again in 2012 (3 holes). The Springlet Lake area is described further under the heading “marginal facies and satellite intrusions”. A joint venture agreement in 2011 gave Minfocus the right to acquire a controlling interest in the Leckie stock and areas extending down the east and west flanks of the Seagull complex, for somewhat more than 50% of the area of the intrusion (Burga, 2011). A rig was mobilized to test four targets in the area of historic drilling in February-March 2012. These drill programs, plus ongoing phases of prospecting and mapping, small-scale pitting, trenching and auger sampling, assaying (including re-assay of some historic core from earlier operators), data compilation, and mineralogical and geometallurgical work comprise the new initiatives summarized below. The company is currently working to complete the third of four years’ work expenditures as its major contribution to earn-in to the project.

**Field Geology**

The degree of exposure is <1%, approaching zero in low, swampy areas. Nevertheless, careful field work has added appreciably to the knowledge of the regional geology, both through district-wide (e.g., Hart, 2005) and property-scale (e.g., Deller and Weston, 2012) surveys. Areas near the margins of the complex display relatively more differentiated or contaminated facies, such as monzogabbro with white and pink feldspars (though some of the latter may possibly be hematized plagioclase, in which case leucogabbro might be a better term). Olivine gabbro or melagabbro to peridotite are appropriate field terms for the bulk of the intrusion at surface, while the dunite best described by Heggie (2005) is seen best and most abundantly at deeper levels, restricted to drill core. The ultramafic rocks are variably serpentinized, fine to medium-grained, bluish-black in freshly-broken faces, and may display a characteristic texture in weathered outcrops (Figure 9.1).

Two short prospecting and mapping visits were paid by the authors to the southwest and north / northeast flanks of the Seagull complex in August-September 2013 (Harper and Wilson, MNDM assessment filings in prep., 2013). Beyond the margins of the complex, as in the southwest of the area, the principal host rock is gneiss, migmatite and granitoids of the late Archean, meta-sediment-dominant Quetico subprovince of the Superior craton. The regional foliation is steeply dipping, striking N60-80ºE. The granitoids can be divided in the field into three suites, namely: a) variably foliated and deformed white granites; b) visually massive reddish granites which are appreciably to strongly magnetic; and c) late, white massive S-type anatectic leucogranites. The latter typically form rounded domes rising several metres or more above the surrounding rocks. They are often pegmatitic, with particularly coarse white feldspars, plus smoky quartz, muscovitic mica, and locally mm- to cm-sized garnets rich in the almandine and spessartine molecules.
Figure 9.1. Roadside outcrop of Seagull peridotite. Note the classic “crocodile skin” weathering of the partially serpentinized rock, seen also in variably-mineralized boulders at Current Lake (Thunder Bay North project, Ontario), outcrop on the Eagle property (Yellow Dog peridotite, Michigan), and elsewhere. The Keweenawan ultramafic rocks display many similarities across hundreds of km (see, e.g., Wilson, 2013).

Figure 9.2. 80-cm-wide, near-vertical dyke of late diabase, with chilled margins, strikes N120°E and cuts coarser diabase of the regional Nipigon suite, just west of the southwest margin of the Seagull complex.
To the east, Mesoproterozoic sediments of the Sibley Group predominate, and form the principal lithologies in scattered outcrops, frequent glacial erratic boulders and cobbles, and the drill core of the Springlet Lake area. The most abundant lithology is an orangey-pink calcareous siltstone, which colours local roadways, such is the local preference for Sibley gravel as roadstone! Subordinate pale grey carbonate sediments also occur, typically forming more angular erratics.

The medium-grained, moderately to quite strongly magnetic diabase of the Nipigon suite is abundant throughout much of the Nipigon embayment northwards from the city of Thunder Bay. The sill frequently encountered in drilling around the Leckie stock, typically ~70-80 metres thick, is part of this suite. Figure 6.2 displays a relatively rare example of a later diabase, injected into the regional sill complex after the latter had cooled sufficiently to generate chilled margins in the incoming late mafic melt.

We can now look in more detail at the igneous lithologies encountered at surface and in drill core.

**Principal Lithologies**

Much of what we have found concerning Seagull stratigraphy has been through four drill holes in early 2012 (Harper and Wilson, 2012a). Subsequently, a total of 30 polished thin sections were prepared from drill core recovered from recent drill holes WM12-35, 36, 37 (23 samples) and historical hole WM08-28 (1 sample). The sections were examined in transmitted and reflected light. 17 sample the Seagull complex itself: 9 dunites, 4 other ultramafic rocks (various named peridotite, lherzolite, websterite or harzburgite, consequent upon visually estimated modal proportions), 3 gabbroic to gabbronoritic rocks, and a rock identified as a melt vein at the basal contact of the intrusion. Seven others represent somewhat younger diabase bodies: the well-documented horizontal Nipigon diabase sheet high in the succession (2 samples) and five from a thick, deep diabase body encountered in hole WM12-37 (Wilson, 2012a).

The major rock types, which could be subdivided further, seen in drill core and outcrop include:

- **Olivine gabbro to melagabbro**: in outcrop, these rocks are distinguished by granular, non-ophitic texture, clear presence of feldspar, and a range of grain size. One example, 30 cm above the footwall contact with Quetico basement near the base of hole WM12-35, is quite coarse, with circa 50% feldspar, abundant pyroxenes (CPX>>OPX), plus primary oxides (magnetite and ilmenite) all altered to non-magnetic leucoxene, plus biotite mica and lesser amphibole, sulphides and quartz, suggestive of wallrock interaction.

- **Peridotite**: quite fine-grained, magnetic, and often dotted with pale to red (hematized) orthopyroxene oikocrysts, the groundmass containing disseminated brown mica. Some examples are feldspar-bearing. Often cut by thin veinlets invested with white calcite and/or magnesite, or by veinlets with dark serpentine and other sheet silicates. May contain >80% olivine and alteration products, transitional to dunite.

- **Dunite**: mostly fine-grained, with olivine ranging from fresh to >90% serpentinized, with oikocrysts of ortho- and clinopyroxenes plus accessory biotite, magnetite, Cr spinel, amphibole and talc.

The following rock types are more localized, but (monzogranite) may be quite extensive in outcrop:

- **Gabbronorite**: attending the late consolidation of the magmatic pile, which was at least several hundred metres thick, was the local expulsion of a relatively evolved melt (previously referred to as felsic dykes?) that may cut the dunitic host rock as vertical sheets or pipes (as opposed to subhorizontal layers or xenoliths?) of relatively pale and coarse-grained rock of gabbroic to gabbronoritic composition, composed of two pyroxenes, strongly altered feldspar(s), biotite mica and magnetite. May contain sulphides, and assay >1 ppm Pt+Pd and 0.2% Cu.
Melt veins: at the base of hole WM12-36, a dark veinlet of unusually magnetic nature was observed within the Quetico granitoid footwall, immediately beneath the Seagull intrusive floor. Composed largely of turbid feldspar, biotite and quartz, such veinlets are interpreted as local partial melts of the leucocratic host rock, possibly infused with an element of Keweenawan melt, charged with sufficient magnetite to be distinct from the host granites (though some of the latter are themselves magnetite-rich).

Monzogabbro: a medium-grained lithology with prominent white and pink feldspars, found as outcrop and glacial float, especially towards the margins of the complex. Most samples are very strongly magnetic due to abundant disseminated magnetite.

The ultramafic units contain late serpentine-magnetite veinlets that may include native Cu, an indication of the strongly reduced nature of the rocks, which show variable uralitization and serpentinization. Early work also noted a saline fluid associated with porous dunite, that may contain hydrocarbons, in rocks which do not appear to dry out, appearing oily long after recovery from the drill hole (Pettigrew, 2002). Such rocks tend to oxidize and disintegrate at an alarming rate in core boxes exposed to air, reminiscent of the degradation of which curators are all too aware, of certain pyrrhotite and marcasite samples, or of metal-silicate interfaces in some stony-iron meteorites. In the Seagull rocks, bravoite (nickeloan pyrite) appears to be the most common sulphide (plus lesser chalcopyrite, pyrrhotite, pentlandite and sphalerite), and the PGM species are a diverse range of mostly S-absent phases. Challenges to the further understanding of these rocks include:

- The fine-grained nature of the generally olivine-dominant primary mineralogy
- Scarcity of well-defined igneous layering and lamination
- Low volumetric abundance and fine grain size of ore minerals
- Poor correlation of sulphide content to precious metal values

The primary and especially the late-magmatic (deuteritic-hydrothermal) mineral assemblage of the predominant ultramafic rocks is quite typical of such rocks (the “peridotite clan”) seen in other mafic-ultramafic intrusions of the Midcontinent Rift. The magmatic suite includes cumulus olivine (major), chromite and magnetite (accessory) and intercumulus (coarsely oikocrystic) pyroxenes (generally orthopyroxene>clinopyroxene). However, the “Midcontinent Rift signature” appears to be a late-magmatic brown amphibole and associated coarse brown mica (titanian biotite or possibly phlogopite) plus fine-grained, deep green (chromian?) chlorite. The ongoing process of cooling in the now largely crystalline intrusion continued with pervasive, locally almost complete serpentinization of olivine, with associated separation of secondary magnetite in olivine, and local precipitation of secondary sulphides and native copper.

Diabase Sills and Dykes

The typical Nipigon diabase is quite distinctive, with classic ophitic texture displayed by the intergrown, volumetrically predominant plagioclase and clinopyroxene. The feldspar commonly exhibits a yellowish-green tinge. The feldspar is white on weathered faces. Outcrops often form steep to vertical scarps and cliffs in the region. The angular jointing typical of diabase of often visible. The upper surfaces of sills may show arrays of angular contraction joints, a variant of columnar jointing. The rocks vary from fine- to medium-grained, the coarser interiors of thick sills at times appearing texturally more gabbroic than a “textbook” diabase. The major sills show upper and lower chilled margins tens of cm thick.

The upper diabase found in drill core, described in numerous past reports, is a sill of Nipigon diabase aspect, which cuts horizontally through the upper portion of the preserved ultramafic sequence of the Seagull intrusion. It displays classic ophitic texture, and is sufficiently evolved to host accessory amounts of finely granular quartz and granophytic mesostasis interstitial to the primary feldspar (labradorite) and clinopyroxene. It
is circa 70-80 m thick, and shows chilled margins against the Seagull rocks above and below (Laarman and Middleton, 2009; Harper and Wilson, 2012a). This sill contains magnetite, partially resorbed ilmenite, and some granophyre ± quartz, apatite, and in some cases a trace of relict, silicate-armoured olivine in the presence of late free silica. A lower diabase, encountered only in some of the deeper historic holes, and in hole WM12-37, displays broadly similar mineralogy, but is subject to much stronger alteration. Both diabase units may contain granophyre and traces of sulphides, including chalcopyrite. The deep diabase is locally quite pyritic, contains more hematite, and may display amphibole-chlorite and/or carbonate veinlets, and accessory anthophyllite.

Figure 9.3. Aeromagnetic map of the Seagull complex, from the “Lake Nipigon Regional Geoscience Initiative” project (see, e.g., Ontario Geological Survey, 2004; Hart, 2005). The area depicted here is some 15 km east-west. The Leckie stock is the magnetic high near the north margin of the Seagull complex, which appears as a subcircular outline. The ENE-trending magnetic high on the southwest side of the complex, underlying the north end of Upper Wolf Lake, is a band of magnetic granitoids of the Quetico subprovince, as noted in the section on “physical properties”.

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Figure 9.4. A schematic east-west section through the northern part of the Seagull complex, showing known horizons of mineralization and known and inferred diabase sheets that post-date the development of the ultramafic stratigraphy. Harper and Wilson, assessment report on the N.E. Seagull claims, in prep. (2013).

**Structural Geology**

The orientation of elongate lakes and drainages provide strong indication of faulting in NNW-SSE and conjugate directions, a direction shared with regional structures such as the Black Sturgeon and Clearwater lakes faults. An aeromagnetic map and schematic cross-section are presented (Figures 9.3 and 9.4). Because of the historical focus on the Leckie stock, past drill programs may have missed the role of horst and graben structures in the distribution of mineralization, particularly in the eastern half of the complex.

**Quaternary Geology**

Surficial deposits are generally thin, apparently often <5 metres, with dark brown soils on the Keweenawan intrusives, and local black sand deposits. Glacial erratics are variably rounded, generally no more than 3 metres in size, and in the case of ultramafic rocks generally angular, presumed to have travelled on the order of 1 km or less. In contrast, rounded blocks of the regional Nipigon diabase sheets are common and presumed to have travelled tens of km, being a very tough lithology, in contrast to local peridotites and visually distinctive but relatively soft sediments of the Sibley Group (both of which are generally angular) to sub-rounded. Glacial striations, best preserved in fine-grained lithologies on northern exposures, indicate a principal, NNE-SSW ice-flow direction near N207ºE, the same as the Current Lake area, 20-30 km to the south.
Mineralogy

The thesis work of Heggie (2005) remains the most detailed examination of the mineralogy of the intrusion. Recent work has included transmitted and reflected light petrography of drill core samples (Wilson, 2012a) and scanning electron microscope (SEM) and petrographic work on trench samples of disaggregated peridotite / black sands (di Prisco, 2012, Wilson, 2012b). A first attempt at a systematic mineralogy for the locality (Seagull intrusion), including silicates, sulphides, oxides and the platinum-group minerals (PGM), is presented in Table 9.1. Selected minerals and textures are shown in Figure 9.5, and PGM in Figure 9.6.

The Seagull ultramafic rocks contain signature gangue minerals noted in thin section at other Keweenawan locations with similar lithologies, including the Eagle and BIC locations in Michigan and Current Lake. In particular, a brown mica (biotite or phlogopite) is almost always found in careful inspection of hand specimens, while in transmitted light an intense green chlorite and a deep-brown, anhedral, late-magmatic amphibole are also present in accessory amounts.

Mineralization

As seen in Figure 9.4, recognized PGE mineralization at Seagull includes at least three vertical levels of diverse styles, which display progressively lower S content upwards, away from the footwall. In addition to these are the secondary “black sands” at surface, erratically enriched to ppm levels of Pt and Pd. A shallower, un-named stock west of the Leckie stock (Laarman and Middleton, 2009) displays the basal mineralization, but not the RGB reef. The near-basal sulphides are seen as forming in dynamic, contaminated magma with early sulphide saturation (like Noril'sk) whereas the RGB reef formed higher and later by classic magma mixing (as in the case of the Bushveld reefs). Although classic igneous phase layering is rare, some secondary processes give the appearance of bands or layers, e.g., serpentine veinlets. There is also a very distinctive magnetite-banded, fine-grained version of dunite / peridotite, with multiple parallel magnetite lamellae spaced at 10-20 mm intervals, the distribution of which has not yet been studied sufficiently to know whether it has stratigraphic significance (e.g., Harper and Wilson, 2012a). The most striking feature of the Seagull mineralization may be the very low sulphide tenor. Sulphides are seldom as much as 1% by volume of the rock, and may be disseminated, in veinlets, or segregated as discrete blebs within the silicate host rocks. The latter sulphide masses may display so-called “parachute texture”, with tops of chalcopyrite- cubanite above bodies of pyrrhotite- pentlandite, a way-up criterion, were one required (e.g., Pettigrew, 2002).
Table 9.1: Systematic Mineralogy, Seagull Complex

The following list compiles observations from outcrop (O), drill core (C) and black sands (S), including thin sections and polished mounts, from the recent work described here, plus all available literature (L, mostly drill-core studies) on Seagull (Wilson, 2012b). The nine PGM in *italics* are recent, provisional species identifications based on observed element associations and other data: they require quantitative microprobe analyses and/or other tests such as micro-XRD or micro-Raman spectra for definitive recognition.

Table 9.1A. Gangue minerals and non-chalcophile, non-PGM ore-mineral species

<table>
<thead>
<tr>
<th>Mineral species</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olivine</td>
<td>O, C, S, L</td>
</tr>
<tr>
<td>Epidote</td>
<td>O, C, L</td>
</tr>
<tr>
<td>Clinopyroxene</td>
<td>O, C, S, L</td>
</tr>
<tr>
<td>Orthopyroxene</td>
<td>O, C, S, L</td>
</tr>
<tr>
<td>Brown, late-magmatic amphibole (kaersutite?)</td>
<td>O, C, L</td>
</tr>
<tr>
<td>Secondary tremolite</td>
<td>O, C, L</td>
</tr>
<tr>
<td>Secondary actinolite</td>
<td>C, L</td>
</tr>
<tr>
<td>Hornblende</td>
<td>C, L</td>
</tr>
<tr>
<td>Anthophyllite</td>
<td>C</td>
</tr>
<tr>
<td>Serpentinite</td>
<td>O, C, S, L</td>
</tr>
<tr>
<td>Phlogopite / Ti-biotite mica</td>
<td>O, C, S, L</td>
</tr>
<tr>
<td>Intense green chlorite</td>
<td>O, C, L</td>
</tr>
<tr>
<td>Talc</td>
<td>O, C, L</td>
</tr>
<tr>
<td>Iddingsite</td>
<td>O, C, L</td>
</tr>
<tr>
<td>Plagioclase feldspar &amp; alteration products</td>
<td>O, C, L</td>
</tr>
<tr>
<td>Quartz / granophyre</td>
<td>C, L</td>
</tr>
<tr>
<td>K-feldspars</td>
<td>O, L</td>
</tr>
<tr>
<td>Chromite</td>
<td>C, S, L</td>
</tr>
<tr>
<td>Magnetite / titanomagnetite</td>
<td>O, C, S, L</td>
</tr>
<tr>
<td>Hematite</td>
<td>C, L</td>
</tr>
<tr>
<td>Ilmenite</td>
<td>O, C, S, L</td>
</tr>
<tr>
<td>Rutile</td>
<td>C</td>
</tr>
<tr>
<td>Leucoxene</td>
<td>C</td>
</tr>
<tr>
<td>Goethite</td>
<td>O, C, S</td>
</tr>
<tr>
<td>Carbonates</td>
<td>C, L</td>
</tr>
<tr>
<td>Apatite</td>
<td>C, L</td>
</tr>
<tr>
<td>Monazite</td>
<td>S, L</td>
</tr>
<tr>
<td>Barite</td>
<td>S, L</td>
</tr>
<tr>
<td>Baddeleyite</td>
<td>S, L</td>
</tr>
<tr>
<td>Zircon</td>
<td>L</td>
</tr>
<tr>
<td>Zirconolite</td>
<td>L</td>
</tr>
</tbody>
</table>
# Table 9.1B. Sulphides, native elements, gold and lead tellurides and assorted PGM species

<table>
<thead>
<tr>
<th>Mineral species</th>
<th>Ideal or schematic formula</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marcasite</td>
<td>FeS₂</td>
<td>O, L</td>
</tr>
<tr>
<td>Chalcopyrite</td>
<td>CuFeS₂</td>
<td>O, C, L</td>
</tr>
<tr>
<td>Cubanite</td>
<td>CuFe₂S₃</td>
<td>L</td>
</tr>
<tr>
<td>Idaitae</td>
<td>Cu₅FeS₆</td>
<td>L</td>
</tr>
<tr>
<td>Fukuchilite</td>
<td>Cu₃FeS₈</td>
<td>L</td>
</tr>
<tr>
<td>Pyrrhotite</td>
<td>Fe₇S₈</td>
<td>O, C, L</td>
</tr>
<tr>
<td>Pyrite</td>
<td>FeS₂</td>
<td>O, C, L</td>
</tr>
<tr>
<td>Bravoite (nickeloo pyrite)</td>
<td>(Fe,Ni)S₂</td>
<td>C, S, L</td>
</tr>
<tr>
<td>Heazlewoodite</td>
<td>Ni₃S₂</td>
<td>L</td>
</tr>
<tr>
<td>Pentlandite</td>
<td>(Ni,Fe)₃S₈</td>
<td>C, S, L</td>
</tr>
<tr>
<td>Violarite</td>
<td>FeNi₂S₄</td>
<td>C</td>
</tr>
<tr>
<td>Millerite</td>
<td>NiS</td>
<td>L</td>
</tr>
<tr>
<td>Galena</td>
<td>PbS</td>
<td>L</td>
</tr>
<tr>
<td>Argentite</td>
<td>Ag₂S</td>
<td>L</td>
</tr>
<tr>
<td>Sphalerite</td>
<td>ZnS</td>
<td>L</td>
</tr>
<tr>
<td>Native copper</td>
<td>Cu</td>
<td>L</td>
</tr>
<tr>
<td>Native silver</td>
<td>Ag</td>
<td>S, L</td>
</tr>
<tr>
<td>Graphite</td>
<td>C</td>
<td>L</td>
</tr>
<tr>
<td>Native gold</td>
<td>Au</td>
<td>L</td>
</tr>
<tr>
<td>Bogdanovite</td>
<td>Au₅(Cu,Fe)₃(Te,Pb)₂</td>
<td>L</td>
</tr>
<tr>
<td>Rucklidgeite</td>
<td>(Bi,Pb)₃Te₄</td>
<td>L</td>
</tr>
<tr>
<td>Altaite</td>
<td>PbTe</td>
<td>L</td>
</tr>
<tr>
<td>Sperrylite</td>
<td>PtAs₂</td>
<td>S, L</td>
</tr>
<tr>
<td>Michenerite</td>
<td>PdBiTe</td>
<td>L</td>
</tr>
<tr>
<td>Kotulskite</td>
<td>Pd(Te,Bi)</td>
<td>L</td>
</tr>
<tr>
<td>Stibiopalladinite</td>
<td>Pd₅₋ₓSb₂₋ₓ</td>
<td>S, L</td>
</tr>
<tr>
<td>Keithconnite</td>
<td>Pd₂₀Te₇</td>
<td>L</td>
</tr>
<tr>
<td>Cu-Pd alloy</td>
<td>CuₓPdᵧ</td>
<td>L</td>
</tr>
<tr>
<td>Merenskyite</td>
<td>PdTe₂</td>
<td>L</td>
</tr>
<tr>
<td>Polarite</td>
<td>PdBi</td>
<td>L</td>
</tr>
<tr>
<td>Mertieite (e.g., mertieite-I)</td>
<td>Pd₁₁(Sb,As)₄</td>
<td>L</td>
</tr>
<tr>
<td>Sobolevskite</td>
<td>PdBi</td>
<td>S, L</td>
</tr>
<tr>
<td>Telluo palladinite</td>
<td>Pd₀Te₄</td>
<td>L</td>
</tr>
<tr>
<td>Testibiopalladinite</td>
<td>PdSbTe</td>
<td>L</td>
</tr>
<tr>
<td>Insizwaite</td>
<td>PtBi₂</td>
<td>S</td>
</tr>
<tr>
<td>Genkinite</td>
<td>(Pt,Pd)₄Sb₃</td>
<td>S</td>
</tr>
<tr>
<td>Ferronickelplatinum</td>
<td>PtFe₀.₅Ni₀.₅</td>
<td>S</td>
</tr>
<tr>
<td>Tetraferroplatinum</td>
<td>PtFe</td>
<td>S</td>
</tr>
<tr>
<td>Palladoarsenide</td>
<td>Pd₂As</td>
<td>S</td>
</tr>
<tr>
<td>Zvyagintsevite</td>
<td>PdₓPb</td>
<td>S</td>
</tr>
<tr>
<td>UNK – unassigned</td>
<td>(Pt,Pd)Bi</td>
<td>S</td>
</tr>
<tr>
<td>Irarsite</td>
<td>IrAsS</td>
<td>S</td>
</tr>
<tr>
<td>Osarsite</td>
<td>OsAsS</td>
<td>S</td>
</tr>
</tbody>
</table>
Figure 9.5A. Springlet Lake area. Selected specimens. A. Angular block, roughly 50 cm in maximum dimension, of an ocellar intrusive rock, some 1.5 km southwest of the south end of Moraine Lake, on the eastern flank of the Seagull complex. Such a boulder has probably not travelled far from its bedrock source due to glacial action, though in this case it may have been moved a short distance by heavy equipment during construction of a forestry road. Photographed in 2005. This block was also figured by Hart (2005, pp.22-23) as a variolitic mafic sill. B. Scanned images of two 46x27-mm polished thin sections of NQ-gauge drill core, in transmitted light, showing spheroidal bodies first thought to be varioles. The spheroids, some just 1-1.5 mm wide, perfectly circular, appear locally to coalesce, and are thought to be liquid-immiscible ocelli of the first melt to enter the magma channel of the sill. Perhaps more Fe-rich, they were immediately dispersed by a second pulse, perhaps more magnesian and Cu-rich. C. An Fe-rich ocellus in sill intersected in 2010 drilling, field of view 2 mm: photomicrograph in transmitted plane-polarized light. D. The pale matrix of such ocelli contains chalcopyrite grains up to 140 µm in size. Field of view 2 mm, photomicrograph in reflected plane-polarized light. E. Core from hole SL08-07, showing ocellar texture in a sill intruding and locally hornfelsing the Sibley strata.
Figure 9.5B. Springlet and Seagull samples. A. Skeletal oxides in Keweenawan satellite sheets, in the immediate west side of the Current Lake chonolith (left) and in thin sheet near Springlet Lake (cf. left side of image C on previous page). B. Scanned transmitted-light image of thin section from Seagull hole WM12-37-322.5, a serpentinized dunite with 1% disseminated and vein-hosted sulphides, mostly bravoite. C. In section, the rock is largely serpentine and lesser magnetite after olivine, field of view 1.7 mm, transmitted, plane-polarized light. D. Sample WM08-28-312.08 m, a mesocumulate dunite with intercumulus orthopyroxene, field of view 1.7 mm, transmitted crossed-polarized light.
Figure 9.6. SEM imagery of PGM (platinum-group minerals). The largest PGM grain, out of 87 found in the 10 polished mounts of black sands, was sperrylite, PtAs$_2$, circa 20 µm in diameter, seen at left in reflected, plane-polarized light, 500X magnification, field of view 0.19 mm, in association with iron oxides on silicates, against smooth mounting medium. The grain and its x-ray energy spectrum are visible in backscattered electron imagery on the SEM control panel, upper right, and close-up, below. A second example (below) is a much rarer Os-(Ir, Pt)-As-S mineral at the interface between silicate and Fe oxyhydroxide gangue phases (di Prisco, 2012).
The sulphides are almost always accessory phases, <1% of the mode and <1 mm in size. They are commonly disseminated in the interstices between cumulus silicate grains, and appear to be relatively late, indicative of precipitation of the associated metals with sulphur at the stage of serpentinization. Impersistent veinlets suggest at least mm-scale mobility of metals at this time. The sulphide phase is dominated by anhedral grains or masses identified, by local tradition, with the nickeloan pyrite variant known as bravoite. Fine-grained chalcopyrite is also widespread. Minor pyrrhotite is also present, plus uncommon traces of pentlandite and sphalerite.

Chromium is located in cumulus spinels (chromite and magnetite), clinopyroxene, and presumed lower concentrations in other primary silicates and secondary silicates such as bright-green chlorite and talc.

The base and precious-metal deportment resides almost entirely in very small (<30 µm) grains of discrete PGM species, requiring sophisticated instrumentation to detect and catalogue (Di Prisco, 2012; Wilson, 2012b). The previously-documented PGM population at Seagull has in the main described drill-core samples from the deeper zones (RGB Reef, basal mineralization). A range of PGM are known, with a variety of tellurides. In contrast, the latest study has involved a concentrate from black sand and its parental, partially disaggregated peridotite within 3 metres of surface over the Leckie stock. Here, tellurides appear curiously absent (Table 1B). It would be premature to conclude whether this apparent difference is due to selective dissolution of tellurides in the weathering environment or is perhaps due to a distinct, peculiarly S- (and Te-) poor mineralogy in the source “reef” that must lie above the extensive diabase sill, within about 60 metres of the current erosion level.

The geometallurgical study on the near-surface PGM (di Prisco, 2012) was conducted on ten polished mounts, prepared from two black sand samples, following a simple crushing and gravity tabling procedure which was undertaken to increase the heavy-mineral content of the sand. The various fractions assayed as high as 494 ppb Pd, 576 ppb Pt and 5600 ppm Cr. Automated scans of each mount were made using an ASPEX PSEM eXplorer scanning electron microscope operated by Dr Giovanni di Prisco of Terra Mineralogical Services Inc., Peterborough, Ontario. Each occurrence of significant concentrations of target elements (such as PGE) was recorded. Subsequent examination of the energy spectra of the secondary x-rays permitted the identification of 87 PGM grains, and generalised observations of the host minerals, which in these sulphur-poor rocks are generally silicates or less often oxides. The samples were run in variable-vacuum mode, uncoated. The PGM were found despite the modest grades notes above, in conjunction with low S (0.02% S in the above-quoted assay). The key findings are as follows:

- Most PGM are at grain boundaries;
- They are not liberated, but attached to grains of silicate or less often iron oxide species, and so accessible (in the current state of crushing and grinding) to solvents and other reagents;
- They are generally very fine-grained, circa 0.5 to 10 µm in diameter, or occur as elongate thin films on grain boundaries;
- The largest grain is a sperrylite, PtAs₂, circa 30 x 22 µm;
- The smaller grains would be very hard or impossible to locate by conventional microscopy, and the automated scans made possible by the latest generation of SEM technology will be key to understanding the geometallurgy of the PGM, in order to optimize PGE recovery from the rock.
- Sperrylite is the most abundant PGM in terms of both area and number of individual occurrences, but a range of Pd-Sb, Pd-Bi, Pd-As and Pd-Pb phases, amongst other PGM, are present. Tellurides appear largely absent, while rare phases include Os-Ir-As-S minerals and native Ag. Thus Pt and Pd, plus minor Os, Ir and Ag were detected, but no Au, Ru or Rh, though these could be present at low percent levels in some of the identified PGM, and not noted in the x-ray energy spectra.
Inferences on the Three-dimensional Structure of the Seaquill Complex

The thick, horizontal diabase sill cutting the Seaquill sequence in the Leckie stock has been known for more than a decade. Re-examination of some of the historic drill logs and of recent hole WM12-37 indicates that there may well be more than one sill, and that they may split or otherwise vary in thickness. A possible interpretation is shown schematically in Figure 9.4. As implied by recent mapping, it may be that the local thicknesses of the complex are largely controlled by the horst-and-graben features which reflect the NNW-SSE fault set.

Marginal Facies and Satellite Intrusions

The monzogabbro near the margins of the Seaquill complex may possibly be influenced to some degree by wallrock assimilation, a process that may also perhaps account for pink feldspathic (“syenite”) veinlets in gabbroic rocks near the east margin of the complex. Skarn and hornfels occurrences have been documented in the Sibley Group sediments in proximity to the intrusion.

Drilling in the Springlet Lake area (Harper, 2011; Harper and Wilson, 2012b) has included 15 short holes testing an area with lake sediment PGE anomalies, with the goal of locating and tracing satellite intrusives eastwards of the Seaquill complex. One or more thin (decimetre- to metre-scale) mafic-ultramafic sills have been found in the area, cutting the calcareous Sibley host strata, which display colourful hornfels development due to limited contact metamorphism around the thin sheets. The sills display evidence of assimilation of wall rock, with local ocellar textures, in some cases containing concentrations of fine-grained, subeconomic but definitely anomalous chalcopyrite (Figure 9.5).

Limitations of geophysical work in the Midcontinent Rift, except in favourable areas such as Current Lake, are imposed by thick and widespread plateaux developed, mesa-like, on laterally extensive diabase sills. Such sills, as we have seen, may also intrude the slightly older ultramafic rocks, and their cumulative magnetic signature will likely serve to obscure smaller but critical features such as the “chonolith”, an interpreted feeder and locus of mineralization at Current Lake.

Lithogeochemistry

The initial drilling and assaying in 2012 focused on a pragmatic, minimal data set, namely Cu-Ni, Pt-Pd-Au, Cr and S, useful for magmatic sulphide deposits (Co could also be added, but is generally less than, and related to Ni abundance, occurring in the much the same host minerals). An extension of this for additional assay work combined a 4-acid, total-dissolution approach with Pt-Pd-Au and an extensive multi-element exploration suite (36 elements). This should be perfectly adequate for exploration needs, though it remains to be seen whether critical values, such as Mg, Al and Na can be converted to equivalent oxide values that are acceptably close to XRF-derived whole-rock analyses, typically reported in refereed journals. Select mineralized intervals have also been analysed for all six PGE plus Au, summarized here (Figure 9.7). In future, bulk geochemical data should help to constrain the mineralogy, and vice versa. Two familiar examples follow...

1. Plagioclase. Based on petrographic data, a first estimate puts the typical feldspar in MCR ultramafic and diabase suites near An60 (labradorite). Such a feldspar is composed of ~53% SiO$_2$, 30% Al$_2$O$_3$, 12% CaO and 4% Na$_2$O, plus 1% of traces of Fe, K, H$_2$O, etc. A rock containing 10 wt.% of this feldspar, the modal proportion separating dunite or peridotite from melagabbro, would thus contain 3% Al$_2$O$_3$ and 0.4% Na$_2$O as a direct contribution from feldspar. 35% of that feldspar, representing the modal border of melagabbro and gabbro, would generate ~10% Al$_2$O$_3$ and ~1.5% Na$_2$O in a bulk analysis.

2. Olivine. Heggie (2005) provided much microprobe data to show that the deeper ultramafic rocks at Seaquill had a rather uniformly magnesian olivine, averaging Fo$_{83}$, whereas mafic rock nearer surface was closer to Fo$_{70}$, and the olivine in the shallow diabase sill varied around a median value near Fo$_{50}$.
Figure 9.7. The averaged 6PGE-plus-gold analyses from 22 samples of core, which were recovered in the four drill holes on the Leckie stock in 2012, are shown below. The analysis involved NiS fire assay followed by instrumental neutron activation (Actlabs). The individual and averaged results all show strikingly similar C1 chondrite-normalized PGE patterns. The average sample has a Pt/Pd ratio of 0.85, which is close to historical means for Seagull (circa 0.87) and consistent with the high, that is to say ~1:1, Pt/Pd ratios found in mineralized Keweenawan ultramafic rocks in the region (e.g., ~1.07 for many samples at the Thunder Bay North deposit at Current Lake). That average analysis includes 1077 ppb total PGE+Au, including 428 ppb Pt, 524 ppb Pd and 27 ppb Au, including maxima of 1640 ppb Pt and 2060 ppb Pd, with 139 ppb Au. The samples were all from deeper, mostly reef-type mineralization at 294 to 401 m down-hole depth. The relatively low contents of the more refractory Os-Ir-Ru are not unexpected, since these elements often occur in PGM hosted in Cr spinels, which are near-ubiquitous, but present only at accessory levels in our Seagull samples.

Physical Properties

The magnetic susceptibility of each drill core has been measured at regular intervals (1.5 m) down-hole, using a ZH Instruments SM-30 unit with a 50-mm circular coil. The same unit is used to measure outcrops (typically 8-12 readings) and grab samples (3 readings). An example of the down-hole variation in magnetic susceptibility (Figure 9.8) is taken from hole WM12-36. In the ultramafic rocks, with their variable serpentinization and generally minimal content of sulphides (particularly pyrrhotite), primary (magmatic) and fine-grained secondary magnetite (formed by olivine alteration upon serpentinitization) are expected to control the response. In the field, magnetic susceptibility is a reliable tool to distinguish the granitoid suites, and recent fieldwork (August 2013) was successful in demonstrating that one extensive N60°E magnetic lineament was due to a belt of magnetic granites in the Quetico belt immediately west of the Seagull complex. This belt is clearly visible in regional maps (Ontario Geological Survey, 2004; see Figure 9.3). Similar granites appear to be quite widespread in the
Quetico belt, and locally display visible concentrations of magnetite.

**Specific gravity** has been determined and checked in both field and laboratory settings for a number of drill-core samples, using the classic Archimedean method. In the laboratory, this is cross-checked with reference materials (quartz and a magnetite-rich iron ore) and temperature-corrected. The diabase tends to be somewhat less altered and denser than the variably serpentinized rocks of the Seagull sequence. The widespread upper sill (hole WM12-34, at 147-165 m, n=3 readings) averages 3.04, while the lower body found in the last drill hole (SM12-37, at 440-517 m, n=23) averages 2.93. An average of all Seagull mafic-ultramafic rocks was estimated at 2.79 (field, n=129) or 2.83 (lab, n=70). Samples with extensive bulk or veinlet-hosted “clay” (sheet silicates ± carbonate) alteration cannot be measured as easily nor reliably in this fashion.

**Evolution**

The Midcontinent Rift ultramafic bodies, including Eva-Kitto, Seagull, Disraeli and Hele in Ontario, are a relatively early feature of Keweenawan magmatism, intruded within the interval 1121-1105 Ma (Hart and Macdonald, 2007). Similar dates have been obtained for the Current Lake and Eagle peridotites. The diabase bodies in the region have been subdivided on geochemical criteria into five suites (Hollings et al., 2007), of which the Nipigon suite is by far the most widely distributed.

The map and section (Figures 9.3-4) display three recognized horizons of bedrock mineralization:

- The basal band(s) are gravity cumulates in the core of the trough (only) and may well coincide with sulphide-enriched Archean basement beneath (the Quetico rocks often contain fracture-hosted pyrite, and may be a better S source than the Sibley sediments).

- The intermediate zones (“RGB reef”) appear to coincide with the widening out of the lopolith and in particular with the emergence of the basal marginal olivine gabbro on the flanks. There is supporting evidence for this from the south-central portion of the complex, with the finding of the most elevated PGE values in melagabbro (Deller and Weston, 2012).

- The upper zone which may be (coincidently) near-parallel to the diabase sill.

It may be that there were two phases of injection of ultramafic magma, one of which filled the lower part of the deep trough, followed by a second one which was much larger and more extensive which has the intermediate PGE zone as its near-basal gravity cumulate horizon, with the olivine gabbro as a marginal phase to this. It is therefore possible that the olivine gabbro does not dip down the edge of the trough as shown in Figure 9.4, but rather extends out across the injection phase boundary.

The section portrays within the graben a thin layer of ultramafic melt, possibly near the source of the thin sills injected into the country rock in the Springlet Lake area.

**Future Work**

While some of the ideas presented here remain speculative, based on available field and drill core data, there are opportunities for near- to medium- term advances to be made, including such projects as the following:

- Auger drilling of black sand areas in the north,
- Shallow diamond drilling of mineralization above the widespread diabase sill,
- Mapping and drill-core analysis to determine the existence of parallel graben structures,
- Characterization of alteration associated with mineralization, and
- Further synthesis of geochemical and ge metallurgical data.
Figure 9.8. Down-hole variation in magnetic susceptibility for vertical hole WM12-36 in the Leckie stock, showing the measured data, corrected for the gauge of drill core, versus depth, with lithological notes from the main drill log (Harper and Wilson, 2012a). Values are in $10^{-3}$ SI units.

**SUMMARY**

Peridotite

Diabase sill, 46.3 to 118.77 m

Peridotite

Troctolite, 151.1 to 166.8 m

Peridotite

Gabbronorite along core axis

Peridotite

Deep diabase, 422.65 m to EOH

More magnetic, more variable than the shallow diabase sill.

EOH, 520.9 m (1,709 feet)
Acknowledgements

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FIELD TRIP 10

Geology and Mineralization of the Thunder Intrusion, Thunder Bay, Ontario

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Introduction

The northern Lake Superior region is host to a large segment of the North American Mesoproterozoic Midcontinent Rift (MCR). Since the discovery of high grade Ni-Cu-PGE mineralization hosted by mafic to ultramafic intrusions at the Current Lake prospect in Ontario, and the Eagle deposit in Minnesota, considerable exploration activity has been focused within the region (Smyk and Franklin, 2007 and references therein). However, the small size of these buried deposits makes them difficult to locate both on the ground and on regional magnetic survey maps (Fig. 10.1).

The Thunder intrusion is a mineralized mafic to ultramafic intrusion located on the outskirts of Thunder Bay, ON, which was explored by Rio Tinto (formerly Kennecott Canada Exploration Inc.) in 2005 and 2007 (Bidwell and Marino, 2007). Rio Tinto currently holds the mineral claims. The intrusion is interpreted to be associated with the early magmatic stages of the MCR based on geochemical similarities to mafic and ultramafic rocks of the Nipigon Embayment (Hollings et al., 2007). However, unlike other mineralized MCR intrusions, the Thunder intrusion has relatively low nickel tenor (< 0.08%) and a large range in PGE tenors (combined platinum-palladium values > 0.5 g/t; Bidwell and Marino, 2007). The intrusion is also the only known mineralised MCR intrusion hosted within the Archean Shebandowan greenstone belt as others north of the United States-Canada border intrude the Mesoproterozoic Sibley Group and/or the Archean Quetico metasedimentary subprovince (Williams et al., 1991; Hart and McDonald, 2007).

Figure 10.1: First vertical derivative magnetic field image of the Thunder intrusion region including a field photograph of the Thunder intrusion buried beneath the overburden of Northwestern Ontario. Geophysical data from Ontario Geologic Survey (2003).
An MSc thesis study conducted by Brent Trevisan (Lakehead University) supervised by Dr. Pete Hollings (Lakehead University) and Dr. Doreen Ames (Geological Survey of Canada) began in Fall 2012. The study is a collaborative between the Geological Survey of Canada, the Ontario Geological Survey, and Lakehead University as part of the Ni-Cu-PGE-Cr project, Targeted Geoscience Initiative-4 (TGI-4; Ames et al., 2012). The main objective is to characterise the petrology, mineralization, and alteration footprint of the Thunder intrusion within the context of the MCR as a whole, in order to identify criteria for targeting buried mineralization. As part of the Precambrian Research Center Professional Workshop Series, the goal of this field trip is to provide another example of a known, albeit small, Ni-Cu-PGE deposit within the Lake Superior Region.

**Regional Geology**

The geology that underlies the field trip area includes rocks of the Shebandowan Greenstone Belt (Fig. 10.2; Williams et al., 1991). The Shebandowan greenstone belt forms part of an ENE trending, semi-continuous chain of granite-greenstone belts known as the Wawa Subprovince (Fig. 10.3; Card & Ciesielski, 1986; Thurston, 1991; Williams et al., 1991). With developments in bedrock geology mapping, geochronology, and geochemistry Stott et al. (2010) proposed a new subdivision scheme for the Superior Province based on the concepts of terrane and domain boundaries. As a result, the Wawa Subprovince has been renamed the Wawa-Abitibi terrane within this nomenclature (Stott et al., 2010). However, for the purpose of this field trip, the traditional subdivisions of the Superior Province established by Card & Ciesielski (1986) will be used.

The Shebandowan greenstone belt consists of three suites of the volcanic and sedimentary rocks including the Burchell, Greenwater, and Shebandowan assemblages (Fig.10.4; Williams et al., 1991). These assemblages are structurally deformed and commonly intruded by mafic sills and gabroic-annorthositic plutons (Williams et al., 1991). Metamorphism grades from lower greenschist to lower amphibolite facies with local contact metamorphic aureoles surrounding Archean plutons (Williams et al., 1991).

The Burchell and Greenwater assemblages are two oppositely facing, steeply dipping volcanic suites that share an inferred fault boundary (Fig. 10.4; Williams et al., 1991). The Burchell assemblage is located north of this boundary and has a northward younging direction whereas the Greenwater assemblage is located south of the boundary and has a southward younging direction (Williams et al., 1991 and references therein). Both suites consist of three volcanic cycles typically consisting of a lower massive to pillowed tholeiitic basalt flow sequence with minor komatiitic flows and an uppermost felsic sequence of calc-alkalic andesite, dacite, and rhyolite units (Williams et al., 1991). Corfu and Stott (1986) established a minimum U-Pb zircon age for the Burchell and Greenwater assemblage at 2733 ± 3 Ma.

Although no exposures have been observed, regional map patterns and contrasting structures suggests an angular unconformity exists between the Shebandowan assemblage and the older Burchell and Greenwater assemblage (Fig. 10.4; Williams et al., 1991 and references therein). U-Pb zircon age determination by Corfu and Stott (1986) established the age of deposition of the Shebandowan assemblage at 2689 ±3/2 Ma. Shegelski (1980) described the Shebandowan assemblage as consisting of a suite of calc-alkalic to alkaline flows and pyroclastic deposits of massive, unsorted volcanic breccias commonly mottled by reddish hematite pigmentation, and a suite of sedimentary rocks consisting of polymictic conglomerate, arkose, mudstone, and jasper-magnetite iron formation.
Figure 10.2: Simplified geological map of the northern Lake Superior region showing the location of the Thunder intrusion (red star). Modified after Pye and Fenwick (1965) and Carter et al. (1973).
Figure 10.3: Subdivisions of the Superior province within the greater Thunder Bay area from Smyk and Franklin (2007).
Figure 10.4: Geologic map of the Shebandowan Greenstone Belt modified after Williams et al. (1991). The Thunder intrusion is situated within the eastern limb of the greenstone belt (red star).

The Thunder Intrusion

The Thunder intrusion forms an approximate overall 800m x 1000m surface expression consisting of two intrusive units: a lower mafic-ultramafic basal unit overlain by an upper gabbroic unit (Fig. 10.5). The contact between the two units is sharp with rare xenoliths of the lower mafic-ultramafic unit within the upper gabbroic unit and a poorly developed chill margin. The lower mafic-ultramafic unit is poorly exposed and outcrops along the northern margin of the Thunder intrusion whereas the upper gabbroic unit forms the bulk of the surface expression of the intrusion. The units of the Thunder intrusion are in sharp contact with the country rock lithologies, have poorly developed chill margins, and commonly contain pods of granophyre and xenoliths of the adjacent wall rock. A contact metamorphic aureole was not observed in outcrop however petrographic studies on drill core samples suggest a <10m wide contact metamorphic aureole with static annealing textures.
Figure 10.5: Preliminary geologic map of the Thunder mafic-ultramafic intrusion and a N-S gabbroic dyke within the eastern Shebandowan greenstone belt.

Figure 10.6: Microscopic photos of A) drill core sample of a clastic metasedimentary rock under reflected light collected ~20cm below the wall rock contact. Feldspar grains display undulose extinction (i.e. evidence of strain); however, the metamorphic fabric has been reset due to the heat from the adjacent intrusion, and B) drill core sample of a clastic metasedimentary rock under plan polarized light collected ~12m below the wall rock contact. Outside the contact metamorphic aureole wall rock lithologies maintain a metamorphic fabric.
The Lower Mafic-Ultramafic Unit

The lower mafic-ultramafic unit consists of three igneous phases from stratigraphic base to top: olivine clinopyroxenite, olivine melagabbro, and olivine gabbro. The gradational contact between rock types has been interpreted to be the result of the evolution of a crystallizing magma. This lower unit extends 800m x 300m along the northern margin of the Thunder intrusion (Fig. 10.5). Drill core observations indicate that the thickness of the lower mafic-ultramafic unit is variable between ~130m and ~260m with olivine clinopyroxenite being the thickest phase up to 160m thick. All three phases display a well-developed cumulate texture defined by fine- to medium-grained subhedral olivine and pyroxene (clinopyroxene>>orthopyroxene) phenocrysts and interstitial plagioclase (Fig. 10.7). Within the interstitial plagioclase, hydrous minerals including biotite, chlorite, and amphibole are hosted but decrease in modal abundances away from the wall-rock contact (Fig. 10.7).

The rare-earth and trace element geochemical pattern of the lower unit is similar to an Ocean Island Basalt (OIB) but with indications of negative high field strength element (HFSE) anomalies. Most samples display a weak negative Zr-Hf anomaly likely caused by crustal contamination during emplacement (Fig. 10.8).

The Upper Gabbroic Unit

The upper gabbroic unit is a massive medium- to fine-grained, subophitic leucogabbro. This unit is approximately 700m x 700m forming the southern part of the intrusion. Drill core observations suggest that the thickness of the upper gabbroic cap increases along its steep southward dip direction from ~220m to ~426m. The primary mineral assemblage of the upper gabbroic unit consists dominantly of plagioclase, clinopyroxene and magnetite with minor amounts of orthopyroxene, olivine, and apatite. The texture is defined by subhedral plagioclase and clustered pyroxene with disseminations of subhedral to skeletal magnetite (Fig. 10.9).

The rare-earth and trace element geochemical pattern of the upper gabbroic unit is also OIB-like but with negative HFSE anomalies. Most samples display a weak negative Zr-Hf anomaly and some display a weak negative Nb anomaly especially sample RTTC-BT-082; a xenolith- and granophyre-bearing leucogabbro (Fig. 10.10). Evidently, the upper gabbroic unit samples are relatively more enriched in light
rare-earth elements than the lower mafic-ultramafic unit samples suggesting more crustal contamination during a later emplacement (Fig. 10.11).

Figure 10.8: Primitive mantle normalized rare-earth and trace element diagram for the lower mafic-ultramafic unit. Normalizing values from Sun and McDonough (1989).

Figure 10.9: Microscopic photos of subophitic leucogabbro of the Thunder intrusion’s upper gabbroic unit. A) Photo under plane polarized light. B) Photo under crossed polarized light.
Mineralization

Ni-Cu sulphide mineralization within the Thunder intrusion is hosted by olivine clinopyroxenite along the lower mafic-ultramafic unit-wall rock contact and is greatest along the northern margin of the Thunder intrusion. The mineralized zone reaches a thickness up to 5m and hosts up to 30% medium- to fine-grained disseminated pyrrhotite > chalcopyrite > pentlandite with minor pyrite, bravoite(?), and sphalerite (Fig. 10.11A). Significant diamond-drill intersections include 20m at 0.22% Cu, 0.06% Ni, 0.25 g/t Pt, 0.29 g/t Pd, and 0.04 g/t Au (Bidwell and Marino 2007). However, mineralization sharply drops to trace fine- to very fine-grained disseminations once outside the mineralized zone with a sulfide assemblage consisting of pyrrhotite and chalcopyrite rarely mantled by bornite (Fig. 11B). No significant diamond-drill intersections within the upper gabbroic unit were discovered (Bidwell and Marino, 2007).

Figure 10.11: Microscopic photos of diamond-drill core samples under reflected light. A) Olivine clinopyroxenite sampled ~20cm above the wall rock contact. Medium- to fine-grained disseminated sulfide assemblage includes mantled pyrrhotite, chalcopyrite, pentlandite, and sphalerite. B) Olivine clinopyroxenite sampled ~80m above the wall rock contact. Trace very-fine grained chalcopyrite and rimmed by bornite.
The Thunder Intrusion and the Midcontinent Rift

The Thunder intrusion is spatially an outlier to the main magmatic expression of the MCR (Fig. 10.2). Hollings et al. (2007) showed that a plot of La/Sm versus Gd/Yb can be used to discriminate intrusive units associated with the MCR (Fig. 10.12). On this diagram both units of the Thunder intrusion plot slightly above the field of the mafic-ultramafic intrusions and sills of the Nipigon Embayment (e.g., Hele Intrusion and Shillabeer Sill respectively). The high Gd/Yb values of the Thunder intrusion suggest a deeper mantle source than the other mafic-ultramafic intrusions of the Nipigon Embayment. Further investigation will focus on comparing the Thunder intrusion with the entire suite of MCR mafic-ultramafic intrusive rocks.

Figure 10.12: Plot of La/Smn vs. Gd/Ybn for both units of the Thunder intrusion, and intrusions of the Nipigon Embayment. Chondrite-normalized ratios calculated from the values of Sun and McDonough (1989). Nipigon Embayment data from Cundari et al. (2013).

Marginal Country Rock

Marginal country rocks have been grouped into three map units: metabasalt with minor metagabbroic and clastic sedimentary rocks, clastic sedimentary rocks, and felsic to intermediate metavolcanic rocks with minor clastic metasedimentary rocks (Fig. 10.5). All marginal lithologies are steeply dipping with an average eastward strike, and are metamorphosed to greenschist facies. Field observations are consistent with the descriptions of Shegelski (1980) and Williams et al. (1991) of the Shebandowan greenstone belt. The felsic to intermediate metavolcanic and metasedimentary rocks are interpreted to be part of the Shebandowan assemblage (Fig. 10.13). The metabasalts along the northern margin of the Thunder intrusion are interpreted to be part of the older volcanic suites, possibly the Greenwater assemblage (Fig. 10.14).
Figure 10.13: Outcrop photograph of A) matrix supported polymictic conglomerate with elongated cobble size clasts, and B) deformed planar bedding with alternating layers of mudstone and siltstone.

Figure 10.14: Outcrop photograph of A) massive metagabbro, and B) amphibole-phyric heterolothic metabasalt.

Field Trip Stops

Three field trip stops have been chosen for this field trip (Fig. 10.15). These will highlight the geology of the Thunder intrusion beginning with mineralized olivine clinopyroxenite (Stop 1), moving up section into olivine melagabbro and olivine gabbro (Stop 2), and finishing with the Thunder Upper gabbroic unit (Stop 3). The stops are located on private land and the owners’ permission is required to access the property. Skidder trails will be used to access field trip stops, please exercise caution.
Stop 1A: Mineralized and Barren Olivine Clinopyroxenite

Location: Trenches outcrop north of Peterson Rd.; UTM NAD 83/16U: 330412E 5378462N

Description: Olivine clinopyroxenite outcrops are commonly found in topographic lows, such as the swampy lowland west of this stop that covers most of the Thunder’s northern margin (Fig. 10.5). Stop 1A provides a trench exposure of barren olivine clinopyroxenite that grades into mineralized olivine clinopyroxenite (Fig. 10.16). The mineralized olivine clinopyroxenite consists up to 15% medium- to fine-grained disseminated sulfides consisting of pyrrhotite > chalcopyrite > pentlandite that are commonly mantling one another and occasionally display a blebby shape, interpreted as evidence of the immiscible sulfide liquid developed during the emplacement of the Thunder intrusion (Fig. 10.17). A sample of the mineralized olivine clinopyroxenite yielded 696.1ppm Ni, 3588.1ppm Cu, 491ppb Pd, 373ppb Pt, and 61.4ppb Au.

Figure 10.16: Photograph of A) Stop 1 trench exposure of barren olivine clinopyroxenite, and B) mineralized olivine clinopyroxenite hand sample.
Stop 1B: Mineralized and Barren Olivine Clinopyroxenite

**Location:** Trench outcrops north of Peterson Rd.; UTM NAD 83/16U 330538E 5378440N

**Description:** Approximately 100m east of Stop 1B in another trench exposure, the mineralization is similar to Stop 1B and provides a good example of the lower mafic-ultramafic unit-wall rock contact relationship. The contact is sharp and the olivine clinopyroxenite lacks a well developed chill margin. The wall rock is a pyrite-bearing mudstone that does not display any obvious signs of contact metamorphism. At the top of the trench barren olivine clinopyroxenite occurs indicating a narrow mineralization zone within the olivine clinopyroxenite.

Stop 2: Olivine Gabbro, Thunder Lower Mafic-Ultramafic Unit

**Location:** Peterson Rd.; UTM NAD 83/16U 330390E 5378301N

**Description:** Traversing southwards from Stop 1 and gradually climbing up topography, the rock type shifts to a medium- to fine-grained olivine melagabbro (Fig. 10.18). This outcrop provides the opportunity to see the cumulate texture characteristic of the Thunder Lower mafic-ultramafic unit and sub-vertical serpentinized fractures.

Figure 10.17: Microscopic photo under reflected light of blebby shaped sulfide assemblage consisting of pyrrhotite, chalcopyrite, and pentlandite within olivine clinopyroxenite.

Figure 10.18: Photo of A) Stop 2 outcrop along Peterson Rd., and B) hand sample of olivine melagabbro.
Stop 3: Upper Gabbroic Unit

Location: Skidder trail south of Peterson Rd.; UTM NAD 83/16U 330259E 5378250N

Description: Continuing to traverse southwards along a skidder trail to Stop 3, the rock type shifts to olivine gabbro. Traversing further along the skidder trail we will pass over the buried contact between the two intrusive units of the Thunder intrusion to an outcrop of the upper gabbroic unit. At this outcrop, boulder sized xenoliths of olivine melagabbro are found within leucogabbro (Fig. 10.19A). There is also a sharp textural change from a cumulate to a subophitic texture. The subophitic texture of plagioclase and clinopyroxene is characteristic of the Thunder intrusion’s upper gabbroic unit (Fig. 10.19B).

Figure 10.19: Photos of A) Stop 3 outcrop exposing a olivine melagabbro xenolith within leucogabbro, and B) hand sample of leucogabbro.

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