Chapter 8

MINERAL POTENTIAL OF THE DULUTH COMPLEX AND RELATED INTRUSIONS

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As discussed in Chapter 2, increased demand and commodity prices for platinum group elements (PGEs) have recently reinvigorated exploration activity in the Duluth Complex and related Keweenawan intrusions in northeastern Minnesota. Known copper-nickel deposits along the base of the complex are being reassessed for their PGE concentrations, and intrusions stratigraphically higher in the Duluth and Beaver Bay Complexes are being evaluated using new models for stratiform PGE mineralization within well-differentiated tholeitic systems. A principal objective of geologic map M-119 is to aid identification of new exploration targets by providing an improved geologic picture of the Duluth Complex and related Keweenawan intrusions.

In this chapter, we document the known mineral deposits of the Duluth Complex and related rocks and assess the potential for discovering similar deposits elsewhere in explorable areas of northeastern Minnesota. The types of mineral deposits considered here include copper-nickel-(PGE) sulfide, stratabound and stratiform PGE, iron-titanium ± vanadium oxide, and silver-cobalt fissure veins. We also discuss the economic significance of the North Shore Volcanic Group in terms of the potential for rare metal mineralization of felsic rocks and, indirectly, the regional potential for sulfide deposits implied by copper and nickel concentrations in mafic volcanic rocks. The following discussion focuses on copper-nickel sulfide and stratabound and stratiform PGE deposits because they hold the greatest potential for an economic discovery.

COPPER-NICKEL-(PGE) SULFIDE MINERALIZATION

The fundamental characteristics of this style of mineralization involve sulfur contamination of mafic magmas by pre-Keweenawan footwall rocks, and mineralization occurring in the vicinity of the basal contact of mafic intrusions. The variants of this style of mineralization that may potentially exist in the Duluth Complex include:

- Disseminated copper-nickel-(PGE) sulfide mineralization in basal contact zones of mafic intrusions
- Massive sulfide mineralization at the basal intrusive contact and in footwall rocks
- Sulfide mineralization in major feeder zones (Noril’sk/Voisey’s Bay-type; Naldrett, 1997)

Only disseminated copper-nickel sulfide mineralization and basal massive sulfide mineralization are presently known to occur in the Duluth Complex and will be described. In the final part of this section, we will discuss the potential for other occurrences of these two types of mineralization and the potential for Noril’sk/Voisey’s Bay-type copper-nickel-(PGE) massive sulfide mineralization in intrusion feeder zones.

Disseminated sulfide mineralization

Large resources of low-grade copper-nickel sulfide ore that locally contain anomalous PGE concentrations are well documented by drilling in the basal zones of the South Kawishiwi and Partridge River intrusions. At least nine subeconomic deposits (Chapter 2, Fig. 2.3) have been delineated in the basal 100 to 300 meters of both intrusions. The mineralization consists predominantly of disseminated sulfides that collectively constitute over 4.4 billion tons of material averaging 0.66 percent copper and 0.2 percent nickel (Listerud and Meineke, 1977). Overall, the copper to nickel ratio averages 3.3:1, ranging from 2.4:1 to 4.11:1 (Chapter 2, Table 2.2). PGE concentrations average about 10 parts per million platinum + palladium (recalculated to 100 percent sulfide), but may range as high as 50 parts per million platinum + palladium (recalculated to 100 percent sulfide) in associated stratabound zones, such as the Birch Lake and Dunka Road deposits. Sulfur isotope analyses consistently indicate that the source of sulfur was from the pelitic country-rocks of the Virginia Formation, which form much of the footwall to the Partridge River intrusion and locally to the South Kawishiwi intrusion (Ripley, 1986).

The sulfide deposits are hosted by taxitic troctolitic to gabbroic rocks that contain abundant
inclusions of the various footwall rock types. Within the Partridge River intrusion, the basal unit (Unit I of Severson and Hauck, 1990; see Chapter 6, Fig. 6.10) hosts the vast majority of the disseminated sulfides. Similarly, mineralization within the South Kawishiwi intrusion is confined to the basal heterogeneous (BH), ultramafic 3 (U3), basal augite troctolite/norite (BAN), and updip wedge (UW) units (Severson, 1994; see Chapter 6, Fig. 6.12). The disseminated sulfide minerals occur as interstitial grains that make up between trace amounts and 10 percent of the rock by volume (visual estimation). The average sulfide mineral content is between 1 and 5 percent. Major sulfide minerals are pyrrhotite, chalcopyrite, cubanite, and pentlandite. Pyrrhotite is generally the dominant sulfide, especially closer to the basal contact. Chalcopyrite is generally the dominant copper-sulfide with variable amounts of cubanite. Also present are minor amounts of bornite, talnakhite, chalcocite, digenite, mackinawite, vallerite, violarite, native copper, and platinum group minerals.

Although this mineralization type is described as being present within the basal units of the South Kawishiwi and Partridge River intrusions, the basal zones do not contain sulfides in all areas. Mineralized zones do not contain sulfides in all areas. Mineralized zones are extremely erratic in their spatial extent and ore grades. Zones that are barren of sulfides commonly interfinger with mineralized zones in a random pattern. This erratic pattern of mineralization, in part, mirrors the lithologic heterogeneity of the basal units. The only exception to this random mineralization pattern is the Maturi deposit (and its down-dip eastward extension), where the upper portion of the basal heterogeneous (BH) unit consistently exhibits copper values in excess of 1.0 percent that gradually decrease with depth toward the basal contact. The change to more consistent mineralization at Maturi may be related to a thinning of the basal heterogeneous unit in the area and thus the sulfides are more restricted to a specific horizon. Although the style of mineralization in all of the deposits is dominated by disseminated copper-nickel sulfides, differences occur between the deposits in copper-nickel and PGE grade, thickness, and tonnage. Mineralization profiles from single drill holes within each of the deposits of the South Kawishiwi intrusion are presented in Figure 8.1. Peterson (2001) attributed the higher-grade, sheetlike mineralization of the Maturi and Maturi Extension deposits to confined magma flow of the lower South Kawishiwi intrusion beneath a large pillar of older anorthositic series rocks.

Contrasting with this heterogeneity of rock types and mineralization, some internal PGE-
bearing sulfide zones within the lower units exhibit a stratabound relationship to the igneous stratigraphic section. For example, at the Dunka Road (Geerts, 1991) and Babbitt deposits, the top of Unit I immediately beneath an ultramafic layer (Fig. 8.2) commonly exhibits increased copper-PGE grades. These PGE-bearing zones are often copper-enriched. Two other stratabound copper-rich (± PGE) zones are present beneath discontinuous ultramafic horizons within the interior of Unit I at Dunka Road (Fig. 8.2). At the Maturi deposit, a copper-enriched (and possibly PGE-enriched) zone also occurs immediately beneath an ultramafic unit (U3) at the top of the basal heterogeneous unit.

Copper-enrichment often occurs locally near fault zones as in the Wyman Creek, Wetlegs, and Dunka Road deposits close to the basal contact (Severson and Hauck, 1997), and at the South Filson Creek deposit, 670 meters above the basal contact (Kuhns and others, 1990). The causes of

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**Figure 8.2.** Distribution of PGE-bearing stratabound horizons relative to the igneous stratigraphy at the Dunka Road deposit (modified from Geerts, 1991).
copper-PGE enrichment along faults are not entirely clear, but probably involve the remobilization and redeposition of copper and PGEs by circulating chlorine-rich hydrothermal fluids, possibly during the latest stages of magmatic crystallization. Evidence for such fluids is given by the presence of chlorine-rich brown liquid drops that commonly coat the surfaces of drill core after exposure to air. These drops form by a deliquescent process and are found on core from the Fish Lake area north to the Spruce Road deposit (Chapter 2, Fig. 2.3) and the Gunflint Trail area. Analyses of the drops indicate high chlorine content values up to 3,000 parts per million (Dahlberg 1987; Dahlberg and others, 1988; Dahlberg and Saini-Eidukat, 1991). The drops are most common on core from the ultramafic layers (variably serpentinized) and the oxide ultramafic intrusions (OUI). They are also locally associated with disseminated sulfide zones, massive sulfides at the Local Boy ore zone of the Babbitt deposit, massive oxides and ultramafic layers from the U3 unit of the South Kawishiwi intrusion, pre-Duluth Complex sills (Logan-type sill and Cr-sill), and olivine-bearing portions of the metamorphosed footwall Biwabik Iron Formation (submembers C and P; see Chapter 4, Fig. 4.3). In addition to the liquid drops, chlorine-rich coatings on the core occur in a variety of colors and precipitate forms. A complete listing of these drill core coatings is included in Hauck and others (1997a).

In summary, the disseminated sulfide mineralization at each of the copper-nickel deposits, with the exception of the Maturi deposit, can be classified as chaotic with diverse ore grades that are unevenly distributed throughout the basal mineralized units. This diverse nature makes it difficult to predict the overall spatial distribution of ore zones based on widely scattered drill holes and little to no outcrop. More in-fill drilling is needed in order to address ore controls. The cause of the erratic mineralization is probably related to a variety of factors that include:

- The nature of magma emplacement (turbulent versus quiescent)
- The mode of emplacement (along bedding planes in the footwall rocks versus overplating previous magma pulses)
- The volume of magmatic inputs (small incremental batches versus wide-spaced and large-volume batches)
- The total sulfide content of the magma prior to final emplacement
- The sulfide content of the footwall rocks (in situ source)
- The secondary enrichment/depletion of copper and PGEs along faults

Magma pulses in the basal heterogeneous units appear to have formed dispersed sulfides that were unable to coalesce and form massive sulfides. Exceptions include pyrrhotite-rich massive sulfides at the Serpentine and Dunka Pit deposits; however, in these two cases a local sulfur source is also present in the footwall Virginia Formation. Most of the disseminated mineralization appears to have formed from a sulfide melt that interacted with low volumes of silicate magma, as indicated by low to moderate R-factors ranging from 50 to 3,000 (Thériault and others, 1997, 2000). The low R-factors are probably the result of close-spaced magma inputs of limited volume in progressively developing magma chambers accompanied by contamination from the footwall rocks. Conversely, the copper-PGE-enriched zones beneath ultramafic horizons formed from a sulfide melt that apparently interacted with large volumes of silicate magma as indicated by high R-factors in the range of 5,000 to 17,000 (Thériault and others, 1997, 2000). The high R-factors of these zones are indicative of more turbulent magma conditions following a new magma input that crystallized the ultramafic layers. Overall, copper- and PGE-enriched zones within the disseminated sulfide mineralization are associated with a dynamic changeover in the style of emplacement from close-spaced, low-volume, and contaminated pulses to wide-spaced, large-volume, and uncontaminated pulses. Some late hydrothermal secondary enrichment of copper and PGEs also took place adjacent to faults during later stages of emplacement.

**Basal massive sulfide mineralization**

In a few localized areas along the basal zones of the South Kawishiwi and Partridge River intrusions, semi-massive to massive sulfide mineralization is present at the basal contact. In most cases, the massive to semi-massive sulfide is proximal to either sulfide-rich footwall rocks or structures such as faults and pre-complex folds. Massive sulfide zones that are spatially related to sulfide-rich footwall rocks are intersected in scattered drill holes in the Dunka Pit, Babbitt, and Serpentine deposits (Severson, 1994; Severson and others, 1994; and Zanko and others, 1994, respectively). All of these massive sulfides are
pyrrhotite-rich (with generally less than 2 percent copper) and are present at, or slightly above, the basal contact. In all cases, a pyrrhotite-rich member of the footwall Virginia Formation (bedded pyrrhotite unit) is located at the basal contact and is situated updip of the massive sulfide occurrences. This relationship suggests that the bedded pyrrhotite unit acted as a local sulfur source that generated a copper-poor, sulfide-rich melt that was concentrated downdip along the basal contact, via gravity settling. An example of this relationship is portrayed in Figure 8.3 for the Serpentine deposit. Pyrrhotite-rich massive sulfides are also present at Water Hen (in both the OUI and troctolitic rocks), Central Boulder Lake, and Fish Lake exploration areas (Chapter 2, Fig. 2.3).

The massive sulfide occurrence in the Local Boy ore zone of the Babbitt deposit (Fig. 8.4) is clearly structurally controlled. At this locality, the massive sulfide zones are copper-rich (generally 5 to 25 percent copper) and are situated along the axis of an anticline defined by the footwall rock units. The highest PGE values (11 parts per million

Figure 8.3. Distribution of semi-massive to massive sulfide zones in drill holes relative to the bedded pyrrhotite member within the Virginia Formation at the Serpentine deposit (modified from Zanko and others, 1994).
Copper-rich (i.e. PO is 50%, Pyrrhotite-rich Pyrrhotite dominant, >85% PO)

1. SEMI-CONTINUOUS MASSIVE SULFIDE HORIZONS ASSOCIATED WITH FOOTWALL ROCKS OR HORNIFELS INCLUSIONS ABOVE THE BASAL CONTACT
   - Pyrrhotite dominant i.e. >85% of sulf. is PO
   - Pyrrhotite-rich i.e. 50-85% of sulf. is PO
   - Upper-rich i.e. Cu is >90%, Cu minerals >30%)

2. WIDELY SCATTERED PODS OF SEMI-MASSIVE TO MASSIVE SULFIDE ASSOCIATED WITH EITHER HORNIFELS INCLUSIONS OR TROCTOLITIC ROCKS
   - Pyrrhotite dominant, >85% PO

Figure 8.4. Potential distribution of semi-massive to massive sulfide types relative to the Grano fault and Local Boy anticlinal axis at the Local Boy ore zone of the Babbitt deposit (modified from Severson and Zanko, unpub. data).
palladium and 8 parts per million platinum) found to date within the Duluth Complex are associated with these structurally controlled, copper-rich, massive sulfides. The massive sulfides are almost exclusively hosted by the Virginia Formation, present as both inclusions above the basal contact and in the footwall rocks below the basal contact, while interfingering intrusive rocks are relatively barren of massive sulfide. These relationships, plus sulfide textures that are indicative of structural preparation, suggest that the massive sulfides were “injected” into the footwall rocks. Ripley (1986) and Severson and Barnes (1991) proposed that an immiscible sulfide melt, formed in an auxiliary magma chamber at depth, was injected into structurally prepared zones in the footwall rocks along the anticline to form the Local Boy ores. Late movement of chlorine-rich fluids along the axis of the anticline further redistributed and concentrated the PGEs (Severson and Barnes, 1991). Recent studies (Severson and Zanko, unpub. data) indicated that there is an overall increase in the copper-PGE content of the massive sulfide in an east-to-west direction (Fig. 8.4); this is possibly the result of fractional crystallization of immiscible sulfide melt as it migrated into the footwall rocks. In this scenario, the north–south-trending Grano fault is inferred to be a potential feeder zone.

Structurally controlled veins and irregular pods of massive sulfide are locally present within granitic footwall rocks immediately beneath the South Kawishiwi intrusion. These occurrences are intersected in scattered holes that outline two northeast-trending belts (Fig. 8.5). The linearity of the belts suggests they are fault controlled. One of these belts crudely aligns with the Birch Lake fault zone that trends through the Birch Lake PGE prospect. The massive sulfide veins were probably formed by the downward expulsion of a basal immiscible sulfide melt into fractured and faulted footwall rocks (Bonnichsen and others, 1980; Severson, 1994). The veins are moderately copper-enriched due to fractional crystallization of the sulfide melt as it moved down through the footwall rocks.

At the Water Hen area (Chapter 2, Fig. 2.3), orthopyroxenite dikelets (possibly structurally controlled) within fine-grained intrusive rocks above the basal contact contain up to greater than 3 parts per million combined palladium + platinum + gold (Morton and Hauck, 1987). Although these occurrences are not massive sulfide, most of the orthopyroxenites are sulfide-enriched, and chalcopyrite is the dominant sulfide. Severson (1995) compared the orthopyroxenite dikelets at Water Hen to the high-grade footwall veins at the Strathcona mine in the Sudbury Complex, Canada. In the Skibo area, there are massive sulfide veins with maximum values of 11.23 percent copper and 6.42 percent nickel that are associated with troctolitic rocks near the basal contact (Severson, 1995).

The occurrence of local massive sulfide veins near and below the basal contact of the Duluth Complex is an indication that larger, potentially economic footwall massive sulfide deposits may yet be found. In the Sudbury Complex, pooling of a monosulfide solid solution (mss) melt at the basal contact appears to be an important prerequisite to the injection of fractionated sulfide melts (Naldrett, 1997). Exploration drilling for basal mineralization rarely penetrated far into footwall rocks beneath the Duluth Complex and therefore data are lacking on the petrochemical attributes of footwall massive sulfides. Peterson (1997) compiled the available copper-nickel data for the lower 500 feet of the South Kawishiwi and Partridge River intrusions to evaluate if copper-rich sulfide melts were generated by fractionation of monosulfide solid solution. He defined some interesting target areas, but a more rigorous evaluation of the database and test drilling into the footwall are needed.

**Feeder zone sulfide mineralization**

Some of the attributes of the Duluth Complex copper-nickel-PGE sulfide deposits resemble those of deposits at Noril’sk, Russia and Voisey’s Bay, Canada that are associated with sulfide mineralization in intrusive feeder zones. The common attributes include occurrence in shallow tholeiitic intrusions associated with plateau basalt volcanism, an external sedimentary source of sulfur, and openness to repeated magma influx and expulsion. A critical attribute of the high-grade Noril’sk–Talnakh and Voisey’s Bay deposits, not yet positively identified in the Duluth Complex deposits, is the location of a magma conduit. A conduit that experienced repeated influxes of magma appears to be key to the formation of high-grade copper-nickel-PGE deposits (Naldrett, 1997). One of the difficulties in evaluating the potential for feeder zone mineralization in the Duluth Complex is determining whether intrusions were fed one-by-one by local magma conduits or by master conduits that sequentially fed several intrusions.
Several geologists have identified possible conduits that may have fed the South Kawishiwi and Partridge River intrusions. Severson and Zanko (unpub. data) suggested that the Grano fault might mark a possible feeder zone for the Local Boy ore zone at the northeast end of the Partridge River intrusion (Fig. 8.4 and Chapter 2, Fig. 2.3). Thériault and others (2000) postulated that a conduit was present somewhere between the Wetlegs and Dunka Road deposits. Another possible feeder zone may have been along the prolongation of the Siphon fault, which is a Paleoproterozoic growth fault (Graber, 1993) that may have been reactivated during emplacement of the Duluth Complex (Severson and Hauck, 1997). Several authors have suggested the presence of a feeder beneath the Bald Eagle intrusion based on field relations (Weiblen and Morey, 1980) and geophysical attributes (Chandler, 1990). A model relating the emplacement of the South Kawishiwi and Bald Eagle intrusions to this single magma feeder is presented in Chapter 6 (Fig. 6.15). At a more detailed level, Peterson (2001) interpreted the copper-PGE mineralization in the Maturi deposit and its extension to the east (Maturi Extension deposit) as indicative of magma input from the northwest via an arcing macrodike that connects the Bald Eagle and South Kawishiwi intrusions (M-

**Figure 8.5.** Linear distribution of massive sulfide, disseminated sulfide, and copper-rich veins in the Giants Range granitic footwall rocks beneath the South Kawishiwi intrusion (modified from Severson, 1994).
Peterson (2001) envisioned a confined magma flow model that invokes a change from laminar to turbulent flow beneath a pillar of older anorthositic series rocks, increasing the R-factor of the entrained sulfides, and resulting in higher metal contents of the exited (Maturi deposit) and remaining (Maturi Extension deposit) sulfide fraction (Fig. 8.6). A down-dip view of the three-dimensional model along the northern margin of the South Kawishiwi intrusion is presented in Figure 8.7. If correct, this model predicts that a Voisey’s Bay-type copper-nickel-PGE massive sulfide body may exist in an area south of the Spruce Road deposit.

Taking a more regional view, it is also possible that the two major Bouguer anomalies record the positions of major conduits that fed layered series intrusions in the Duluth Complex and some hypabyssal intrusions in the Beaver Bay Complex (Chapter 3, Fig. 3.5 and Chapter 4, Fig. 4.6). Geophysical models indicate depths of mafic rocks to more than 10 kilometers over these anomalies (Allen and others, 1997). If these intrusive roots represent the master conduits to most Duluth

Figure 8.6. Simplified conceptual model of magma flow and copper-nickel-PGE deposits for the northern South Kawishiwi intrusion.
A. Copper-nickel deposit location map overlain on a three-dimensional model of the basal contact of the South Kawishiwi intrusion (Peterson, unpub. data).
B. Magma flow model.
C. Plan view of the turbulent magma flow under the anorthositic series pillar (AN Block).
D. Cross-section of the turbulent magma flow under the anorthositic series pillar (AN Block).
Complex intrusions, it suggests that potential feeder-zone sulfide mineralization may exist at prohibitive depths.

**New copper-nickel-(PGE) sulfide mineralization targets**

Most of the mineral exploration conducted along the base of the Duluth Complex over the past 60 years has focused on copper-nickel potential. As mentioned earlier, many of the established copper-nickel sulfide deposits (Chapter 2, Fig. 2.3) are presently being reevaluated for their PGE concentrations (see Chapter 2), but this work is only beginning. In addition to this reevaluation of known areas of mineralization, other underexplored and unexplored areas of the Duluth and Beaver Bay Complexes hold potential for copper-nickel-(PGE) sulfide mineralization.

Intriguing exploration targets in the otherwise heavily explored basal contact zone of the Duluth Complex are the Sudbury-like copper + PGE-rich sulfide offshoot veins in footwall rocks. Most prior exploration drilling, being focused on copper-nickel sulfide mineralization within the intrusive rocks, stopped when the footwall was reached. As mentioned above, a few longer drill holes and reconnaissance mapping have shown the presence of footwall sulfide vein systems in the Giants Range granite (Severson, 1994). A study of copper-nickel concentrations in the basal zones of the Partridge River and South Kawishiwi intrusions (Peterson, 1997) showed areas of copper enrichment and depletion that may imply fractionation and mobilization of sulfide melt. Peterson (1997) speculated that zones of copper depletion may indicate downward migration of copper + PGE-rich sulfide melt, and therefore the footwall beneath such depleted areas may host offshoot veins. Such targets may be especially inviting where the depletion overlies known footwall structures.

Farther into the Duluth Complex, intrusions were emplaced largely within volcanic rocks or previously formed intrusions. Thus, potential sources of sulfur contamination are lacking, at least at the level of emplacement. Possible exceptions to this are those intrusions emplaced adjacent to the northwest-trending Schroeder–Forest Center ridge that gives rise to the pronounced saddle in the Bouguer anomaly over northeastern Minnesota (Chapter 3, Fig. 3.3). This crustal ridge, which is probably a projection of the Archean Giants Range batholith, appears to have acted as a deflecting rampart to several layered series intrusions (the Bald Eagle, Wilder Lake, and Greenwood Lake intrusions; see Chapter 4, Fig. 4.6). In the northern Beaver Bay Complex, successive dike-like intrusions appear to have intruded along the southeast termination of the ridge or along the same breach in the ridge. Although the general

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**Figure 8.7.** View to the south–southeast down the dip of the basal contact of the northern margin of the South Kawishiwi intrusion. A possible Voisey’s Bay copper-nickel-PGE massive sulfide target is interpreted to occur at the western end of the macrodike connecting the Bald Eagle and South Kawishiwi intrusions.
composition of this ridge appears to be granitic, it also contains metavolcanic and metasedimentary rocks, indicated by the presence of inclusions of amphibolite and biotite schist in the Shoepack Lake diorite (Boerboom, 1994)—the earliest intrusion of the Beaver Bay Complex (Chapter 7). Consequently, the potential exists for this crustal ridge to have been a source of extramagmatic sulfur for some Duluth Complex and Beaver Bay Complex intrusions.

Duluth Complex intrusions that may have developed basal zone sulfide mineralization due to interaction with the Schroeder–Forest Center crustal ridge include the Bald Eagle intrusion (northern margin), the Wilder Lake intrusion (basal zone), and the Greenwood Lake intrusion (eastern extension). Of these, only the Greenwood Lake intrusion is in an explorable area outside the Boundary Waters Canoe Area Wilderness. Of the intrusions of the northern Beaver Bay Complex, the basal zones of the Wilson Lake ferrogabbro and offshoot dike, the Dam Five gabbronorite, the Elbow Lake olivine gabbro, and the northwestern margin of the Houghtaling Creek troctolite may be potential targets where they cut across the crustal ridge. These intrusions may also have derived sulfur from the Whitefish Lake granophyre body in the roof zone of the Duluth Complex.

STRATABOUND AND STRATIFORM PGE MINERALIZATION

PGE-enriched zones in the Duluth Complex and related intrusions can be classified into two categories—stratabound and stratiform. The term stratabound refers to PGE-enriched horizons that are restricted to a general stratigraphic unit; however, the PGE-enriched zones are often transgressive relative to the enclosing stratigraphy because they are associated with a wide variety of internal rock types that characterize the stratigraphic unit. The term stratiform denotes specific PGE-enriched horizons that are sheetlike in form, concordant, and strictly coextensive with laterally persistent igneous layers. Stratabound PGE horizons are located within the lower portions of the intrusions where they are intimately associated with copper-nickel sulfide mineralization and with one or more ultramafic layers that indicate magma recharge events. The stratiform PGE horizons differ from the stratabound ones because they are consistently sulfide-poor and tend to occur at midlevels of well-differentiated intrusions. The origins of the two types also differ because stratabound PGE horizons appear to be related to magma mixing and hydrothermal remobilization, whereas stratiform PGE horizons tend to form by the saturation of magmas in sulfide caused by orthomagmatic processes of fractional crystallization, decompression due to magma venting, cumulus phase changes, as well as magma recharge.

Stratabound PGE mineralization

Stratabound PGE-enriched horizons, with low to moderate sulfide concentrations (0.05 to 1.0 weight percent sulfur), are commonly associated with ultramafic layers in the Dunka Road, Babbitt, Wetlegs, and Birch Lake deposits (Chapter 2, Fig. 2.3). Elevated copper and PGE concentrations at the Dunka Road deposit, and to a lesser extent the Babbitt and Wetlegs deposits, occur at the extreme top of Unit I immediately beneath a laterally persistent ultramafic layer. At Dunka Road, this stratabound horizon (red horizon of Geerts, 1991, 1994) averages about 10-meters-thick and contains an average of 1.0 part per million palladium + platinum (Fig. 8.2). Recent work by Thériault and others (1997, 2000) suggested that the sulfur was largely derived from the mafic magma and that this stratabound horizon was formed as a result of magma mixing. Two similar stratabound PGE-enriched horizons, related to laterally discontinuous ultramafic layers (Fig. 8.2), occur toward the middle of Unit I at Dunka Road (orange and yellow horizons of Geerts, 1991, 1994). To the west of Dunka Road, the stratabound PGE horizon at the top of Unit I is also present at the Wetlegs and Wyman Creek deposits. In those areas, however, the overall palladium content in this horizon exhibits a definite decrease in an east-to-west direction, suggesting that as the magma was intruded it became progressively impoverished with respect to PGEs (Severson and Hauck, 1997; Thériault and others, 1997).

PGE-enriched stratabound horizons associated with ultramafic layers situated above the basal contact also occur at the Dunka Road and Wetlegs deposits (Geerts 1991, 1994; Severson and Hauck, 1997). Both of these occurrences span across the ultramafic layer that separates Units VI and VII (Fig. 8.2). Further to the south in the Water Hen area, one drill hole intersected a layered ultramafic package that contains a 20-centimeter-thick semimassive oxide (chromium titanomagnetite) layer assaying 780 parts per billion platinum. This occurrence is also positioned well above the basal contact. A similar semi-massive oxide occurrence
associated with ultramafic layers with anomalous PGEs was also cut by a drill hole in the Fish Lake area, located near the base of the Duluth layered series (Sassani, 1992; Severson, 1995).

Another example of a PGE stratabound horizon is at the Birch Lake PGE prospect within the South Kawishiwi intrusion. There, PGE contents as high as 9 parts per million palladium + platinum, and Cr$_2$O$_3$ contents locally as high as 10 weight percent are associated with a wide variety of rock types within the U3 unit. The U3 unit consists of alternating troctolitic and ultramafic layers in which variably sulfide-mineralized zones and discontinuous pods of Cr-bearing massive oxide both occur (Severson, 1994). As stated in Chapter 6, the massive oxide pods are interpreted based on empirical relationships to have been produced by assimilation and partial melting of the Biwabik Iron Formation. This oxide-rich partial melt may have initially acted as a trap that concentrated chromium and titanium, and through further assimilation and contamination of the magma, may have led to precipitation of PGEs. However, because the ultramafic layers of the U3 unit are interpreted to record new influxes of more primitive magma (Severson, 1994), magma mixing may have had a more significant effect on PGE mineralization. Stable and radiogenic isotope data suggest that both magmatic and footwall contamination processes were active at Birch Lake (Hauck and others, 1997b).

Furthermore, the presence of chlorine-rich drops on the surface of drill core from the Birch Lake area suggests that a hydrothermal model of concentrating the PGE could also be invoked. A model involving ascending chlorine-rich hydrothermal fluids, depicted in Figure 8.8 and similar to a model proposed by Boudreau and McCallum (1992), may have remobilized and further concentrated the PGE along the northeast-trending Birch Lake fault (Severson, 1994). Late granophyre bodies and footwall massive sulfide veins (Fig. 8.5) situated preferentially along the fault zone imply that the fault was repeatedly reactivated during emplacement of the South Kawishiwi intrusion (Severson, 1994; Hauck and others, 1997a).

Dahlberg (1987) suggested that PGE-mineralizing fluids at the Birch Lake area were structurally controlled not by the Birch Lake fault but by inferred northwest–southeast crosscutting structures that are evident in the regional gravity and aeromagnetic data. In summary, the mineralization style in the U3 unit at the Birch Lake area is still poorly understood and appears to be related to a magmatic process, coupled with footwall contamination, that was later modified by hydrothermal activity along a northeast- and/or northwest-trending fault zone. Exploratory drilling is ongoing at Birch Lake and concepts pertaining to the origin of the PGEs change as new information is collected.

**Stratiform PGE mineralization**

**Model**

Recent discoveries of gold- and PGE-enriched horizons (or PGE reefs) in the upper part of the Skaergaard intrusion (Bird and others, 1991; Andersen and others, 1998) and related Tertiary intrusions of east Greenland (Aranson and others, 1997) have stimulated exploration for such deposits in other tholeiitic layered intrusions such as those comprising the Duluth Complex. Stratiform PGE mineralization in well-differentiated tholeiitic intrusions are similar to classic PGE reef deposits hosted by ultramafic-mafic complexes, such as the Bushveld and Stillwater Complexes, in that they occur as sulfide-poor (less than 1 weight percent),
PGE-rich intervals that are several meters thick and are conformable with igneous layering. However, stratiform PGE mineralization in tholeiitic intrusions, termed Skaergaard-type PGE mineralization by Prendergast (2000), differs from the classic PGE reefs because it is:

- Exclusively associated with mantle plume-influenced, continental rift environments
- Of Middle Proterozoic age or younger
- Associated with aluminous, olivine tholeiitic parent magma compositions that experience Fenner-type crystallization differentiation
- Hosted by ferrogabbroic cumulate rocks
- Associated with copper-rich, nickel-poor sulfide
- Associated with significant gold that is stratigraphically offset above peak PGE concentrations

Although there is considerable disagreement about how classic PGE reefs formed (Cawthorn, 1999), most believe that Skaergaard-type reefs are orthomagmatic (formation by the saturation, exsolution, and settling of sulfide melt from silicate magma). Boudreau and Meurer (1999) gave the only notable objection to an orthomagmatic model for Skaergaard-type PGE mineralization, arguing instead for a hydrothermal origin.

**Figure 8.8.** Schematic diagram showing the possible role that the Birch Lake fault may have played in funneling upward-moving, chlorine-rich solutions and the resultant re-concentration of significant magmatic PGEs within the U3 unit at the Birch Lake PGE area within the South Kawishiwi intrusion (modified from Severson, 1994). BH—Basal heterogeneous unit, BAN—Basal augite troctolite/norite unit, U3—ultramafic 3 unit.
The key requirements for the orthomagmatic formation of an economic PGE reef in a tholeiitic intrusion are:

- The parent magma must be initially sulfide-undersaturated
- The parent magma must have a high initial PGE concentration and/or experience a considerable amount of fractional crystallization to build up noble metal concentrations prior to sulfide saturation
- The initial segregation of sulfide melt must be associated with a large R-factor (silicate/sulfide melt ratio)

These required conditions imply that the best chance for significant stratiform PGE mineralization in a tholeiitic intrusion should be at a mid- to upper-level horizon that marks the first “cumulus arrival” of immiscible sulfide melt.

Given a well-differentiated, initially sulfide-undersaturated tholeiitic intrusion, its ability to form an economic PGE reef depends on the manner by which sulfide becomes saturated in the magma. To maximize the PGE grade, sulfide saturation should be triggered in such a way that the exsolved sulfide melt is exposed to the greatest volume of silicate melt (Naldrett, 1989b). In this way, dense droplets of sulfide melt can efficiently scavenge PGEs and other chalcophile metals from the silicate magma as they settle to the cumulate floor of the magma chamber to form a stratiform horizon. Chlorine-bearing deuteric fluids may have an important effect on improving the PGE tenor of sulfide ore, and such a hydrothermal process is most effective where it acts on a magmatically generated sulfide-enriched horizon. Mechanisms that may trigger sulfide saturation include:

- **Fractional crystallization**—Because sulfur is an incompatible element in silicate minerals, sulfide will become enriched in differentiating magmas ultimately to the point of saturation and exsolution.
- **Magma recharge and mixing**—Unlike variable sulfide solubility in ultramafic-mafic magmas that produce classic PGE reefs (Naldrett, 1989b), sulfide solubility in differentiating tholeiitic magmas remains fairly constant over the course of fractional crystallization due to the offsetting effects of temperature and Fe-enrichment (Haughton and others, 1974; Naldrett, 1989a; Poulson and Ohmoto, 1990). Therefore, mixing of magmas with comparable sulfide solubilities is unlikely to produce sulfide saturation or oversaturation. Magma mixing probably works in the formation of stratiform PGE mineralization described above because it also involves sulfide contamination in recharging PGE-rich magmas by basal sulfide-bearing units.

- **Decompression due to magma venting**—At shallow crustal depths, sulfide solubility appears to positively correlate with pressure (Carroll and Rutherford, 1985; Naldrett, 1989a). Consequently, in a magma that is close to sulfide saturation, decompression due to magma venting can potentially trigger system-wide exsolution of sulfide melt.

- **Phase changes**—The cumulus arrival of a mineral phase that abruptly lowers the iron content of the magma can potentially trigger sulfide saturation. Magnetite crystallization would be the most effective phase change. This was the apparent trigger for sulfide saturation in the Rincón del Tigre magma system (Prendergast, 2000).

Most intrusions of the Duluth and Beaver Bay Complexes formed from initially sulfide-undersaturated magmas and show evidence of having undergone one or more of the above-mentioned processes during crystallization. Two of these intrusions, the Sonju Lake intrusion (Miller, 1999) and the layered series at Duluth (Miller, 1998a, b), have been studied for their potential to host stratiform PGE mineralization, and subeconomic mineralization has been found in both areas. The Sonju Lake intrusion was a closed magmatic system and the layered series at Duluth was a more open magmatic system. Studies conducted thus far provide exploration guides for finding PGE reefs in associated Keweenawan intrusions. The salient features of PGE mineralization in these two intrusion types are outlined below and the section concludes with guides for stratiform PGE mineralization exploration.

**Stratiform PGE mineralization in the Sonju Lake intrusion**

The Sonju Lake intrusion is a 1,200-meter-thick, shallow-dipping, sheetlike intrusion that forms part of the Beaver Bay Complex (Chapter 7). Although its exposed strike-length is only about 3 kilometers, the Sonju Lake intrusion has a distinctive aeromagnetic signature that can be traced for at least 20 kilometers beneath a cover of glacial drift (Chapter 7, Fig. 7.2). The nearly constant width of its aeromagnetic anomaly
suggests that the intrusive sheet retains a fairly uniform thickness and dip angle over most of this distance. The eastern margin of the Sonju Lake intrusion is abruptly truncated by a Beaver River diabase dike. The base of the Sonju Lake intrusion is in intrusive contact with a complex mixture of gabbroic to dioritic rocks, granophyre, and volcanic hornfels. The top of the Sonju Lake intrusion is in gradational contact with a granophyric quartz ferromonzodiorite phase of the Finland granite. The granite is thought to have acted as a density barrier that caused the Sonju Lake intrusion mafic magma to underplate it (Miller and Chandler, 1997).

The Sonju Lake intrusion is predominantly composed of well-laminated, mafic mesocumulates that define a unidirectionally differentiated sequence. Between a lower contact zone of fine-grained melatroctolite cumulates (unit slmt—OP cumulate, M-119) and an upper zone of un laminated olivine ferromonzodiorite (unit slmd, M-119), five units are distinguished on the basis of cumulus mineral assemblages (Fig. 8.9) and are shown on map M-119. In ascending order these units are: sld—dunite (O), s1t—troctolite (PO), slg—gabbro (POC), slfg—ferrogabbro (PCF ± O), and slad—apatite olivine ferrodiorite (PCFOA). This cumulus stratigraphy is complemented by a smooth cryptic variation in mineral compositions (Chapter 7, Fig. 7.4).

The parent magma composition of the Sonju Lake intrusion is estimated to be an uncontaminated, moderately evolved olivine tholeiite. Miller and Ripley (1996) calculated the bulk composition of the Sonju Lake intrusion by a weighted sum of its chemostratigraphy, and by using fractional crystallization models (for example Nielsen, 1990), they demonstrated that this composition is a reasonable estimate of the parent magma. Similar modeling of the cumulus stratigraphy and cryptic variation suggests that the Sonju Lake intrusion formed by unidirectional fractional crystallization under nearly closed conditions.

To determine the possible location of a stratiform PGE reef in the Sonju Lake intrusion, a total of 67 outcrop and drill core samples that profile the intrusion were analyzed for platinum, palladium, gold, sulfur, copper, and other major and trace elements (Miller, 1999). These data indicate that a narrow PGE-enriched interval exists within the ferrogabbro unit (slfg, M-119) and lies immediately below the stratigraphic level marking the initial saturation of sulfide melt in the Sonju Lake intrusion magma. Measuring stratigraphic height in the Sonju Lake intrusion relative to the horizon where cumulus augite appears (s1t—slg unit boundary, Fig. 8.9), initial saturation and segregation of sulfide melt is inferred to occur at the +322-meter level, where an increase in copper abundance is recognized (Fig. 8.9). Copper content increases from consistently less than 100 parts per million below the +322-meter level to greater than 500 parts per million above, and then gradually decreases to below 100 parts per million in the upper part of the intrusion. This pattern is consistent with:

- Sulfide undersaturated conditions below the +322-meter level
- The saturation and “cumulus” segregation of sulfide melt at the +322-meter level
- The gradual depletion of copper abundance due to continued exsolution of sulfide melt above the +322-meter level

Nickel was strongly depleted in the magma at the time of inferred sulfide saturation, presumably by prolonged olivine crystallization.

Interestingly, the onset of sulfide saturation at the +322-meter level implied by the abrupt increase in copper abundance is not reflected in the sulfur data (Fig. 8.9). Theoretically, a gabbro cumulate saturated in sulfide melt should contain a minimum of 400 parts per million sulfur based on sulfide solubility of 0.1 weight percent for a moderately evolved mafic magma (Haughton and others, 1974; Boudreau and McCallum, 1992). The sulfur abundance in cumulates below the +322-meter level are consistently less than the theoretical saturation benchmark. However, sulfur concentrations above the +322-meter level vary unsystematically between less than 100 and 500 parts per million, and only sustain greater than 400 parts per million sulfur concentrations above about +460 meters. Petrographic observations confirm that this zone of presumed sulfide saturation is locally poor in modal sulfide and where present, the sulfide is dominated by copper-rich varieties (chalcopyrite, bornite, and digenite). A possible explanation for the high copper, low sulfur samples in the zone between +322 meters and +460 meters is that oxidizing deuteric fluids caused dissolution of sulfur without mobilizing copper. A similar oxidation/desulfurization process has been noted in the low-sulfide PGE reefs in eastern Greenland intrusions (Skaergaard,
Figure 8.9. Chemostratigraphic variations in whole rock concentrations of sulfur, nickel, copper, palladium, platinum, gold, and copper/palladium through the Sonju Lake intrusion. Sample height is measured relative to the level of cumulus augite arrival (maaa—meters above cumulus augite arrival). The abrupt increase in copper concentration at the 322-meter level is interpreted to indicate sulfide. Data from Miller (1999).
Andersen and others, 1998; Kap Edvard Holm, Aranson and Bird, 2000). The Sonju Lake intrusion displays several features that are consistent with such a process of oxidation and desulfurization:

- Moderate degrees of chloritic and uralitic alteration of pyroxene are common in ferrogabbroic cumulates of the ferrogabbro (sifg, M-119) unit
- Copper-rich sulfides (chalcopyrite, bornite, and digenite) predominate in samples near the +322-meter level
- Secondary veins of pyrite with hematite occur locally above the +322-meter level

If deuteric desulfurization is a widespread phenomenon in mafic layered intrusions, variations in copper abundance rather than total sulfur may be better indicators of magmatic sulfide saturation.

There are no overt changes in lithology evident from field observations across the horizon of increased copper abundance (and PGE enrichment) that would suggest sulfide saturation was triggered by a significant perturbation to the magma system (such as magma recharge, assimilation, or venting). The only notable change observed across the horizon of initial sulfide saturation is the gradual changeover from titanomagnetite-dominated to ilmenite-dominated cumulus oxide phases. However, this also seems an unlikely triggering mechanism because such a change should have minimal effect on the FeO content of the magma and thus sulfide solubility.

Rather, given the well-differentiated and closed nature of the Sonju Lake intrusion system, it is concluded that simple crystallization differentiation was the process primarily responsible for not only driving the magma to sulfide saturation, but also for triggering the initial sulfide exsolution event.

Palladium consistently peaks in abundance and the ratio of copper to palladium shows an abrupt increase near the +322-meter horizon of initial sulfide saturation (Fig. 8.9). Concentrations of platinum and gold show similar though less regular trends. In the lower two-thirds of the intrusion, where copper values are consistently less than 100 parts per million, palladium values average around 2 parts per billion and range between 0.7 and 5 parts per billion. Estimating that the lower Sonju Lake intrusion mesocumulates contain about 30 weight percent trapped liquid component (Miller and Ripley, 1996), the average 1 to 3 parts per billion concentrations of palladium observed in the cumulates below +230 meters (Fig. 8.9) imply a parent magma concentration of 3 to 10 parts per billion. This is an undepleted concentration that is consistent with observed abundances in plume-related basalts (~7.6 parts per billion palladium, Barnes and others, 1993). Upward from about the +230-meter level, palladium abundance increases regularly to a peak concentration of 320 parts per billion in the sample just below the first known sample to display an abrupt jump in copper to greater than 500 parts per million (see Miller, 1999, Table 1). This high palladium sample also yields the greatest platinum concentration (66 parts per billion), although a secondary platinum peak (less than 30 parts per billion) seems to exist about 90 meters below the sulfide saturation level. The highest gold concentration (85 parts per billion) occurs 35 meters above the level of initial sulfur saturation, although its variation is less systematic than palladium and platinum (Fig. 8.9). In the first high-concentration copper sample (greater than 500 parts per billion) and in most overlying samples, palladium and platinum abundances drop to below detection limits (less than 0.1 part per billion).

The efficiency with which PGEs were scavenged from the Sonju Lake intrusion magma with the “cumulus arrival” of sulfide melt is indicated by the $10^4$ increase in copper/palladium observed across the +322-meter horizon (Fig. 8.9). Changes in the copper/palladium ratio reflect the fact that the sulfide melt/silicate magma partition coefficient for palladium is several orders-of-magnitude greater than that for copper (Peach and others, 1990). The copper/palladium versus palladium variation in the Sonju Lake intrusion (see Miller, 1999, Fig. 7) implies that each aliquot of sulfide melt in the initial sulfide segregation event encountered over $10^5$ times that volume of silicate magma. Such an implied R-factor suggests that an even more PGE-enriched horizon may exist in the 7-meter-thick interval between the sample with peak palladium concentration and the overlying sample with increased copper abundances. Detailed geochemical sampling must be conducted to ascertain the thickness and peak grade of the Sonju Lake intrusion reef.

When directly comparing the Sonju Lake and Skaergaard intrusions, not only are their petrologic similarities evident, but also when comparably scaled, their patterns of precious metal and sulfide mineralization are remarkably similar (Fig. 8.10).
Their similar paragenetic sequences of cumulus minerals imply comparable closed-system crystallization differentiation of aluminous, olivine tholeiitic parent magmas. Based on a 400 parts per million sulfur benchmark and/or increases in copper abundance, both parent magmas were initially sulfide-undersaturated and became saturated at proportionally similar levels in their crystallization histories. Both intrusions were crystallizing a cumulus mineral assemblage of plagioclase + augite + iron oxide at the time of sulfide saturation. Both show peak PGE concentrations at or just below the level of initial sulfide saturation. Both show low and variable levels of palladium in the lower sulfide-undersaturated part of the intrusions (related to variable amounts of trapped undepleted magma) and almost complete and persistent palladium depletion above the sulfide saturation horizon (Fig. 8.10). Finally, both show an upward displacement of peak gold concentration from the PGE peak.

**Stratiform PGE mineralization in the layered series at Duluth**

The layered series at Duluth is a 3.5- to 5-kilometer-thick, sheetlike, mafic layered intrusion that was emplaced into the base of a 4- to 5-kilometer-thick edifice of comagmatic flood basalts, and forms the southernmost layered series intrusion of the Duluth Complex. Intrusion of the layered series at Duluth was preceded by the emplacement of plagioclase crystal mushes that statically crystallized anorthositic series rocks now forming the hanging wall to the layered series at Duluth. The igneous stratigraphy of the layered series at Duluth is divided into five major zones shown on map M-119. Above a basal contact zone of taxitic olivine gabbro and troctolite (unit dlsb, M-119), the main cumulate sequence of the layered series at Duluth progresses upward from PO cumulates of the troctolitic zone (unit dlsr, M-119) to multiphase PCF ± O ± A cumulates of the gabbro zone (unit dlsr, M-119). This cumulative progression
occurs in a cyclical manner across a 1-kilometer-thick interval termed the cyclic zone (unit dlsc, M-119). Upper gabbroic cumulates, in turn, grade upward into unlaminated (noncumulate) apatitic quartz ferromonzodiorite, which composes most of the upper contact zone (unit dlsu, M-119). The ferromonzodiorite complexly mixes with a fine-grained biotitic ilmenite ferrodiorite, which ultimately forms the “chilled” contact with anorthositic series rocks. A body of melanogranophyre (unit dlsm, M-119) that cuts irregularly through the anorthositic series probably represents the uppermost differentiate of the layered series at Duluth. This igneous stratigraphy is complemented by cryptic layering of cumulus mineral compositions (Chapter 6, Fig. 6.8 and Fig. 8.11) and together these imply the layered series at Duluth generally formed by bottom-up fractional crystallization of a moderately evolved, olivine tholeiitic parent magma.

The repeated progression from troctolitic to gabbroic cumulates in the cyclic zone (Fig. 8.12) indicates that the layered series at Duluth, unlike the Sonju Lake intrusion, did not crystallize as a closed system. The cyclic zone consists of at least six major macrocycles (each 50- to 200-meters-thick) within which troctolitic (PO) cumulates grade upward to gabbroic (PCFO) cumulates. Macrocycle boundaries are marked by the abrupt regression in the cumulus paragenesis from gabbroic back to troctolitic cumulate assemblages. The gabbroic parts of the macrocycles commonly contain anorthositic series inclusions and the very uppermost parts of the macrocycles locally have discontinuous layers of fine-grained gabbroic adcumulate (microgabbro). This cyclicity in phase layering does not correspond to a complimentary cryptic variation in mineral chemistry (Miller and Ripley, 1996). Based on these characteristics, Miller and Ripley (1996) suggested that the macrocyclic

![Diagram](image_url)

Figure 8.11. Stratigraphic variation in sulfur, copper, copper/palladium, and palladium + platinum abundances through the layered series at Duluth.
Figure 8.12. Geology and internal structure of the southern part of the layered series at Duluth cyclic zone showing locations and platinum + palladium concentrations in hand samples. Cyclical alternations between three general cumulate rock types define six macrocycles (I-VI).
phase layering is predominantly related to devolatilization and decompression that attended magma venting events from a shallow (less than 5 kilometers) chamber, with magma recharge possibly having a secondary effect.

Geochemical data were acquired from 83 hand samples that profile the general stratigraphy of the layered series at Duluth. The sampling focused on specific horizons, particularly in the cyclic zone, that contain visible sulfide mineralization or appear to represent perturbations to the magmatic system (Fig. 8.11). Most of the samples have platinum + palladium concentrations below 15 parts per billion, 14 samples have concentrations between 15 and 150 parts per billion, and five samples have concentrations greater than 150 parts per billion. Whole rock sulfur and copper concentrations (Fig. 8.11) imply that the layered series at Duluth was consistently sulfide-undersaturated during troctolite-zone crystallization, achieved intermittent saturation during crystallization of the cyclic zone, and was fairly consistently saturated as the gabbro zone accumulated. In contrast to the singular large increase in copper abundance and copper/palladium ratio observed in the Sonju Lake intrusion system (Fig. 8.9), the layered series at Duluth shows erratic variability in these parameters (Fig. 8.11). Such variability probably reflects the openness of the layered series at Duluth system to magmatic recharge. Nevertheless, a 2- to 3-orders-of-magnitude range in the copper/palladium ratio through the cyclic zone indicates at least a low level of efficiency in the ability of sulfide melt to extract PGEs from silicate magma (for example Maier and others, 1996).

Six hand samples that contain the most enriched platinum + palladium and sulfide concentrations come from the upper portions of macrocycles I and II (Figs. 8.11 and 8.12), and the two highest values are associated with gabbro-microgabbro interfaces. The model of magma venting to explain the phase layering of the cyclic zone (Miller and Ripley, 1996) also can explain the elevated concentrations of sulfide and PGE at cyclic zone boundaries of cumulus regression. Experimental data at low pressures (1 to 2 kb) suggest a positive correlation between pressure and sulfide solubility in hydrous tholeiitic magmas (Carroll and Rutherford, 1985). If valid, this implies that magma decompression due to venting from shallow differentiated magma chambers may trigger sulfide saturation (or oversaturation in a saturated magma). Devolatilization resulting from the venting of a volatile-rich magma would also cause an abrupt increase in $fO_2$, which would have a compounding effect on reducing sulfur solubility (Poulson and Ohmoto, 1990). The attractiveness of magma venting as a trigger for sulfide saturation in terms of PGE enrichment is that it would promote chamber-wide sulfide segregation if the system was well-mixed, or a rain of sulfide out of the roof zone if the magma chamber was compositionally zoned. Both situations would promote high R-factors, although the second scenario would require enough overproduction of sulfide to withstand the descent to the cumulate floor.

**Exploration for stratiform PGE deposits in northeastern Minnesota**

The basic conditions required to generate stratiform PGE mineralization imply that all initially sulfide-undersaturated, well-differentiated, tholeiitic mafic layered intrusions can potentially host PGE reef deposits. This is true whether the magma systems are open or closed. Intrusions related to igneous provinces generated by mantle plumes appear to hold the greatest potential to make PGE reefs by virtue of their more PGE-rich composition; however, prolonged fractional crystallization prior to sulfide saturation can theoretically compensate for intrusions formed from parent magma with low initial PGE concentrations.

The stratigraphic position of sulfide saturation and a possible PGE reef in a mafic layered intrusion is difficult to discern by field observations because a sulfide-saturated gabbro need only contain 0.1 weight percent sulfide (Boudreau and McCallum, 1992). As geochemical studies of the Sonju Lake intrusion and layered series at Duluth show, the stratigraphic variability of copper and sulfur can be used as indicators to where sulfide saturation occurred in the crystallization history of an intrusion and may alone be sufficient to locate a favorable horizon for a PGE reef. However, because iron-sulfide may be readily mobilized by deuteric fluids, copper variability may be a better indicator of primary sulfide saturation. Parameters such as the copper/palladium ratio (Fig. 8.11) provide qualitative indicators of the efficiency with which PGEs were scavenged from the magma (Barnes and others, 1993; Maier and others, 1996). Absolute abundances of PGEs have limited use in identifying horizons of initial sulfide saturation because their anomalous concentration will be
tightly bound to the horizon itself, and because evidence of depleted concentrations will require high-resolution analyses (0.1 to 0.5 part per billion detection limits). To properly evaluate any chemostratigraphic data, however, it is important to understand the petrologic history of each intrusion.

For intrusions that fractionally crystallized under generally closed conditions, exploration for stratiform PGE mineralization involves a fairly straightforward process of identifying the level at which the magma became initially saturated in sulfide. If the system is truly closed, the highest PGE concentrations possible should occur at the horizon of initial sulfide saturation. This is certainly the case for stratiform PGE mineralization in the Sonju Lake and Skaergaard intrusions. However, it is unlikely that any intrusive system is completely closed. Even the Skaergaard intrusion, considered the prime example of a closed magmatic system, may have been open to minor recharge or venting events given the cyclical nature of the PGE mineralization and cumulate lithologies associated with the Platinova reefs (Anderson and others, 1998).

In open magmatic systems, exploration should also focus on locating the horizon of initial sulfide saturation. The first significant sulfide saturation/exsolution event has the greatest chance of encountering the most PGE-enriched silicate magma. Moreover, the lowermost sulfide-rich horizon would be best situated to having its PGE tenor upgraded by the fluxing of a deuteritic, chlorine-bearing fluid devolved from the cooling cumulate pile below (for example Barnes and Campbell, 1988; Boudreau and McCallum, 1992). The higher this horizon of initial sulfide saturation is stratigraphically, the greater the likelihood that the primary PGE tenor of the magma was high and the greater the thickness of lower cumulates that could have been scavenged. However, such a horizon may be difficult to identify if sulfide saturation was triggered by a short-term perturbation to the system (such as venting or recharge). Where intrusive systems are known to be approaching sulfide saturation, petrologic indicators of such perturbations should be evaluated (such as abrupt changes in cumulus mineralogy or texture, and the appearance of modal layering). Such an approach was successful in identifying stratiform PGE and sulfide mineralized horizons in the cyclic zone of the layered series at Duluth.

Although the lowest stratigraphic horizon marking sulfide saturation may be the first place to seek out PGE mineralization in an open magmatic system, a lack of significant PGE enrichment at that level should not discourage exploration at higher levels. What matters more to forming a high-grade PGE reef than the overall PGE tenor of the magma at the time of a particular sulfide saturation event is the fluid dynamics of how and over what stratigraphic distance the sulfide melt settled to the floor of the intrusion. In an open magma system where multiple sulfide saturation events may occur, it may be that the fluid dynamics of a later (stratigraphically higher) saturation event was triggered by a process that was more conducive to efficiently scavenging PGEs. Such a situation apparently occurred in the Great Dyke, where the high-grade PGE reef is associated with the Main Sulfide Zone, located some 50 meters above the first sulfide saturation event that formed the PGE-poor Lower Sulfide Zone (Prendergast and Wilson, 1989). Clearly, a full understanding of the crystallization history of a layered intrusion is as important to evaluating its potential for stratiform PGE mineralization as is a thorough geochemical profiling.

**Other exploration targets for stratiform PGE mineralization in northeastern Minnesota**

In addition to the Sonju Lake intrusion and layered series at Duluth, northeastern Minnesota contains a number of well-differentiated, tholeiitic intrusions that are also possible exploration targets for stratiform PGE mineralization. Given that such distinct intrusions as the layered series at Duluth and the Sonju Lake intrusion were both initially sulfide undersaturated, it can be reasonably presumed that most intrusions of the Duluth and Beaver Bay Complexes were similarly undersaturated at the time of their emplacement. The well-differentiated intrusions that occur in explorable areas of northeastern Minnesota include:

- The large, layered series at Duluth-like Greenwood Lake intrusion in the upper-central part of the Duluth Complex
- The small, plug-like Osier Lake intrusion also in the central Duluth Complex
- The Boulder Lake intrusion in the south-central part of the Duluth Complex with its two major differentiation cycles
- The Cloquet Lake layered series forming the western part of the Beaver Bay Complex,
which also appears to be composed of two major differentiation cycles
- The Houghtaling Creek troctolite macrodike, which contains a differentiated sequence in its northeastern extent

With the exception of the Houghtaling Creek troctolite, which is fairly well exposed in the northern Beaver Bay Complex (Boerboom and Miller, 1994; Miller and others, 1994), all other intrusions are poorly exposed to unexposed and are known mainly from their aeromagnetic signatures and scattered drilling (Meints and others, 1993; Miller and Chandler, 1999; Chandler, 2001). Although some hesitancy may exist for exploring such unexposed intrusions, the stratiform nature of this style of mineralization may require only a single geochemical profile to evaluate the sulfide-saturation character of an intrusion and to focus on a favorable horizon for detailed sampling. It might also be possible to conduct geophysical surveys across the igneous stratigraphy of these intrusions to delineate changes in sulfide and/or oxide content.

In early 2002, the Minnesota Geological Survey will conduct a shallow drilling program across the Greenwood Lake intrusion to better determine its igneous stratigraphy and to approximate where sulfide saturation may have occurred in the magma system. The Greenwood Lake intrusion is 6- to 7-kilometers-thick and has aeromagnetic signatures akin to the layered series at Duluth. Therefore, an open magma system model, like the layered series at Duluth, will be used to evaluate its chemostratigraphy. The results of this study will be released in 2002.

Ironically, the two intrusions where most PGE exploration activity has been focused until now, the Partridge River and South Kawishiwi, may hold the least potential for the type of stratiform PGE mineralization described here. These open-system intrusions apparently did not differentiate beyond olivine-plagioclase (troctolite) crystallization (Miller and Ripley, 1996) and were contaminated by extramagmatic sulfur upon emplacement. The stratabound PGE mineralization found at the Birch Lake prospect in the South Kawishiwi intrusion and others noted in the preceding section is not the same type of mineralization described here. Rather, its formation appears to have involved processes of magma recharge, iron-formation assimilation, and late stage remobilization by chlorine-brines along fault zones.

Fe-Ti (± V) MINERALIZATION

Titaniferous iron oxide bodies 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). Over the last 100 years, demands for iron and titanium have periodically stimulated small exploration efforts in the form of outcrop examinations and drilling campaigns. Most of these efforts have taken place along the northwestern margin of the complex in Cook County. Grout (1949-1950) 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 to 14 percent TiO₂ (Hauck and others, 1997a). Oxide mineralization is also associated with late plug-like oxide ultramafic intrusions (OUIs) along the western margin of the Duluth Complex. The oxide ultramafic intrusions were initially discovered by drilling rocks associated with magnetic highs during copper-nickel exploration (Bonnichsen, 1972; Hauck and others, 1997a). Listerud and Meineke (1977) estimated that 220 million tons of oxide material, with greater than 10 percent TiO₂, are present in at least three of the oxide ultramafic intrusions. However, nine additional areas portrayed as oxide ultramafic intrusions in Figure 2.3 (Chapter 2) are known to contain titaniferous iron ores and are not included in their original estimate. Hauck and others (1997a) have classified the titaniferous ores, composed principally of ilmenite and/or titanomagnetite, into three general types: iron-rich metasedimentary inclusions, magmatic banded oxide segregations, and oxide ultramafic inclusions.

Iron-rich metasedimentary inclusions

This category pertains to titanium-bearing inclusions of the Biwabik and Gunflint Iron Formations that occur along the northwestern and northern margin of the Duluth Complex. The inclusions range from those that possess easily recognizable metasedimentary attributes to those that are featureless, pod-like bodies of massive oxide (Hauck and others, 1997a). Examples of the latter are the “restite” pods of Biwabik Iron Formation within the U3 unit of the South Kawishiwi intrusion. Several authors (Broderick, 1917; Grout, 1949-1950; Grout and others, 1959; Muhich, 1993) have concluded that the titanium in the inclusions was added from the surrounding
magma during emplacement of the Duluth Complex. However, not all of the massive oxide zones within the Duluth Complex can be attributed to iron-formation inclusions. Isotope work by Hauck and others (1997b) suggested that some of the oxide-rich zones within the U3 unit, especially the uppermost oxide-rich zones of the unit, might be magmatic in origin. In addition, the spatial relations of subhorizontal oxide-rich horizons located well above the basal contact of the Duluth Complex at the Wetlegs, Water Hen, and Fish Lake deposits (Severson, 1995; Severson and Hauck, 1997) also suggest a magmatic origin. In summary, the effects of partial melting and recrystallization on the iron-formation inclusions may make them extremely difficult to distinguish from magmatic oxide-rich layers. Because these inclusions are of limited extent and thickness, and because they are scattered randomly throughout the basal margin of the Duluth Complex, there have been no attempts to calculate the potential Fe-Ti resources they contain.

**Magmatic banded oxide segregations**

Massive to semi-massive oxide layers of ilmenite and/or titanomagnetite that range in thickness from a few centimeters to 3 meters occur in many places within the Duluth Complex. These layers commonly alternate with plagioclase-rich bands and ferrogabbroic cumulate layers. Both the oxide layers and the enclosing cumulate rocks generally exhibit a primary igneous plagioclase foliation. Individually, the oxide layers commonly grade into gabbroic cumulates both vertically and laterally. Collectively, the oxide layers form a quasi-continuous megalayer, or series, of overlapping lenses that is several kilometers in strike length and dips slightly to the southeast. As mentioned above, this type of oxide occurrence overlaps with the recrystallized iron-formation inclusions, and at some localities it is difficult to discriminate between the two. However, spatial relationships (great thicknesses above the basal contact) indicate that magmatic semi-massive oxide layers are present within the Boulder Lake, Western Margin, and Poplar Lake intrusions, and the Brule Lake–Hovland gabbro. The known oxide-rich horizons contained within each of these intrusions are briefly discussed below.

Probably the best-known occurrences of this category are the Fe-Ti oxide-rich layers within the Poplar Lake intrusion and Brule Lake–Hovland gabbro. Broderick (1917) was the first to make detailed descriptions of oxide-rich zones within the Duluth Complex. Much of his work is included in a later, more detailed study by Grout (1949-1950), who described the geology and conducted a small drilling campaign in 1947 to calculate possible titaniferous resources. Grout (1949-1950) referred to the oxide-rich belt in the Poplar Lake intrusion as the “North Range” and the oxide-rich belt of the Brule Lake–Hovland gabbro as the “South Range.” The North Range encompasses a 24-kilometer-long belt south of the Gunflint Trail and includes exposures along the shores of Poplar and Tucker Lakes (unit plox, M-119). Several test pits were dug into titaniferous-rich material near both lakes, but the exposures on Tucker Lake appeared to be more Fe-Ti rich, and exploratory holes were drilled by the Johnson Nickel Mining Company as early as 1899 (Grout, 1949-1950). However, the early drilling was inadequate to define the grade and amount of material in the deposit and Grout (1949-1950) drilled an additional eight holes at Tucker Lake. Many of these holes intersected variably mineralized “ore zones” that contained as much as 25 percent TiO₂. Even though Grout (1949-1950) believed that the mineralized zones were erratic both mineralogically and spatially, he calculated that the drilling defined a combined 25 million tons of material in a main zone (average grade of 22 percent TiO₂) and two low-grade zones (average grade of 12 percent TiO₂). Today most of the North Range is surrounded by the Boundary Waters Canoe Area Wilderness, and it is unlikely that mining could ever take place on this belt.

Fe-Ti oxide-rich layers of the South Range were also explored by test pits at the same time as the North Range. Rocks of the South Range (unit bhfg, M-119) are exposed in a 10-kilometer-long belt that extends from Smoke Lake on the west to Homer Lake on the east. Grout (1949-1950) drilled two holes at Smoke Lake in 1947, mainly to illustrate that the oxide-rich rocks of the South Range dip to the south, and continue to an unknown depth beneath a large sill-like granite body of the felsic series (unit fgpu, M-119). He estimated that collective resources of the South Range amount to 14 million tons (grades were not specified). However, today this area is also located entirely within the Boundary Waters Canoe Area Wilderness and is not open to mining. Even though Grout (1949-1950) considered the titaniferous ores of the South Range to be magmatic, he noted that outcrops at the east end of the belt might have been contaminated by the Gunflint Iron Formation. A map in his report
showed a belt of “altered Animikie sediments” (unit Psb, M-119) to the immediate north of the South Range at its eastern end. Davidson (1977d) and Davidson and Burnell (1977) also noted these same metasedimentary rocks and, on the basis of chemical analyses, suggested they are similar to the Virginia Formation. As discussed in Chapter 4, a footwall ridge of pre-Keweenawan rock may extend into this area and may have contributed Paleoproterozoic xenoliths to superjacent Duluth Complex intrusions.

Semi-massive to massive oxide layers have been intersected by drilling in the Boulder Lake intrusion at the Boulder Lake North area (Chapter 2, Fig. 2.3). The oxide layers are titanomagnetite-rich, range from 0.02- to 1.5-meters-thick, and are associated with ferrogabbroic cumulates that contain clinopyroxenite lenses (Severson, 1995). Ferrogabbroic cumulates that contain 5 to 10 percent titanomagnetite are also present in the Western Margin intrusion at the Boulder Creek exploration area. Magmatic semi-massive oxide layers from 0.06- to 2.0-meters-thick are also present at the Wetlegs, Water Hen, and Fish Lake areas (Severson, 1995; Severson and Hauck, 1997). There are no known calculations pertaining to Fe-Ti resources for any of these oxide occurrences.

**Oxide ultramafic intrusions (OUIs)**

Exploratory drilling for copper-nickel mineralization encountered several oxide ultramafic intrusions that later were evaluated for their Fe-Ti ± V potential. Many of the oxide ultramafic intrusions are expressed as aeromagnetic highs, commonly with an associated electromagnetic conductor, and thus they were initially drilled in search of conductive sulfide mineralization. At least thirteen oxide ultramafic intrusions have been intersected in drill holes along the basal contact of the Duluth Complex. Detailed drilling to define potential Fe-Ti ± V resources has taken place at only the Longnose and Water Hen localities, and to a much lesser extent at the Section 34 locality. Resources are only known for the Longnose oxide ultramafic intrusion and total approximately 25 million tons of material with greater than 15 percent TiO₂ (Hauck and others, 1997a). Detailed descriptions of the oxide ultramafic intrusions are found in Mainwaring (1975), Mainwaring and Naldrett (1977), Severson and Hauck (1990), Linscheid (1991), Miner and Pasteris (1994), Miner (1995), and Severson (1995).

The oxide ultramafic intrusions are plugs or pipe-like bodies that commonly have irregular apophyses. They intrude troctolitic rocks of the Partridge River, Western Margin, and Boulder Lake intrusions. The Water Hen oxide ultramafic intrusion appears to be rootless as defined by detailed drilling (Fig. 8.13); the three-dimensional configurations of the other oxide ultramafic intrusions are unknown due to insufficient drilling (Hauck and others, 1997a). In general, the oxide ultramafic intrusions are spatially arranged along linear trends, suggesting that structural control was important to their genesis. All of the oxide ultramafic intrusions are crosscutting with the exception of the oxide ultramafic intrusion at Boulder Creek, which is roughly stratabound with a crosscutting feeder zone. Rock types include coarse-grained to pegmatitic clinopyroxenite, dunite, peridotite, melatroctolite, and minor melagabbro; all rock types are oxide bearing. Some oxide ultramafic intrusions exhibit a crude zonation from an olivine-rich core (dunite, peridotite, and melatroctolite) to an outer clinopyroxenite margin, whereas others consist of only one dominant rock type. A thick saprolite cap, presumably formed by weathering during the Cretaceous period, is present at the Water Hen oxide ultramafic intrusion.

Oxide content is variable in the oxide ultramafic intrusions and ranges from 15 percent in disseminated zones to 100 percent in localized massive oxide zones. Oxide ultramafic intrusions that contain thick intervals of massive oxide include Longnose (up to 30-meters-thick; Linscheid, 1991) and Section 34 (up to 40-meters-thick; Severson, 1995). Titanomagnetite is dominant in some of the oxide ultramafic intrusions, whereas ilmenite is dominant in other oxide ultramafic intrusions. Sulfide minerals (predominantly pyrrhotite) are ubiquitous in all the oxide ultramafic intrusions and range from trace amounts to 5 percent in disseminated zones to greater than 70 percent in localized net-textured and massive sulfide zones, such as Water Hen and Boulder Lake South (Chapter 2, Fig. 2.3).

Average and maximum TiO₂ values for each of the thirteen oxide ultramafic intrusions that have been drilled are listed in Table 8.1. In this table, the oxide ultramafic intrusions are divided into two major groups, a northern group (N-OUI) that contains oxide ultramafic intrusions located within the Partridge River intrusion, and a southern group (S-OUI) that contains oxide ultramafic intrusions located in the Western Margin and Boulder Lake intrusions. The N-OUI group do not differ
Figure 8.13. Simplified cross-section of the Water Hen area showing the crosscutting relationship of the oxide ultramafic intrusion to the troctolitic host rocks of the Partridge River intrusion. Also shown are massive sulfide zones and the saprolite cap (modified from Severson, 1995).
appreciably in content of TiO$_2$ from the S-OUI group. The N-OUI group appears to contain somewhat more chromium than the S-OUI group, and somewhat less vanadium. However, the sampling campaigns have differed significantly from one oxide ultramafic intrusion to another, and the data should be interpreted cautiously. Copper values are generally low (less than 0.4 percent) for both the N-OUI and S-OUI groups with the exception of the Water Hen body, which has copper values as high as 1.97 percent associated with massive sulfide intervals.

Other major differences and similarities between the N-OUI and S-OUI groups are listed in Table 8.2. One major difference is the dominant oxide type. Ilmenite is dominant in the N-OUI and titanomagnetite is dominant in the S-OUI (with the exception of the Boulder Lake South oxide ultramafic intrusion). This difference may be related to the mode of origin for specific groups of oxide ultramafic intrusions.

The genesis of the N-OUI group has been empirically linked to intrusion and assimilation of the Biwabik Iron Formation at depth followed by upward movement of an Fe-rich partial melt along fault zones. The Section 17, Longear, and Longnose oxide ultramafic intrusions occur along a northeast-trending fault where the iron-formation is in direct contact with the Duluth Complex (Severson and Hauck, 1990). The oxide ultramafic intrusions from the Wyman Creek deposit southward to the Water Hen oxide ultramafic intrusion (Chapter 2, Fig. 2.3) are associated with a north-trending magnetic high that is interpreted to reflect a strong magnetic overprint caused by heating of the Biwabik Iron Formation (Bath, 1962;
Table 8.2. Summary of major features relative to the oxide ultramafic intrusions (OUIs) in the Partridge River, Western Margin, and Boulder Lake intrusions.

<table>
<thead>
<tr>
<th>Oxide ultramafic intrusion</th>
<th>Oxides, I = ilmenite, M = magnetite</th>
<th>Chromium titanomagnetite</th>
<th>Graphite</th>
<th>Sulfides (in addition to pyrrhotite, cubanite, chalcopyrite, pentlandite)</th>
<th>Apatite</th>
<th>Dominant rock type</th>
<th>Host rock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section 17</td>
<td>I ≥ M</td>
<td>no</td>
<td>bornite</td>
<td>no</td>
<td>pyroxenite</td>
<td>Units VI, VII of prmz*</td>
<td></td>
</tr>
<tr>
<td>Longgear</td>
<td>I ≥ M</td>
<td>no</td>
<td>bornite, pyrite</td>
<td>no</td>
<td>pyroxenite</td>
<td>Units VI, VII of prmz</td>
<td></td>
</tr>
<tr>
<td>Longnose</td>
<td>I ≥ M</td>
<td>no</td>
<td>bornite</td>
<td>no</td>
<td>pyroxenite, pyroxyenite-rind</td>
<td>Units VI, VII of prmz</td>
<td></td>
</tr>
<tr>
<td>Wyman Creek</td>
<td>I &gt; M</td>
<td>yes</td>
<td>no</td>
<td>maucherite, parkerite</td>
<td>no</td>
<td>peridotite, pyroxenite</td>
<td>Unit I of prmz</td>
</tr>
<tr>
<td>Section 22</td>
<td>I &gt; M</td>
<td>yes</td>
<td>no</td>
<td>maucherite, safflorite, cobaltite, sphalerite</td>
<td>no</td>
<td>peridotite, pyroxenite</td>
<td>Unit V of prmz</td>
</tr>
<tr>
<td>Skibo</td>
<td>I &gt; M</td>
<td>yes</td>
<td>yes</td>
<td>maucherite, pyrite, no mackinawite, sphalerite, bornite</td>
<td>no</td>
<td>peridotite, pyroxenite</td>
<td>Unit V of prmz</td>
</tr>
<tr>
<td>Skibo-South</td>
<td>I &gt; M</td>
<td>yes</td>
<td>yes</td>
<td>maucherite, pyrite, no mackinawite, sphalerite, bornite</td>
<td>no</td>
<td>peridotite, pyroxenite</td>
<td>Unit V of prmz</td>
</tr>
<tr>
<td>Water Hen</td>
<td>I &gt; M</td>
<td>yes</td>
<td>abundant</td>
<td>maucherite, pyrite, mackinawite, sphalerite, bornite</td>
<td>no</td>
<td>pyroxene-upper half, peridotite-lower half</td>
<td>Unit V of prmz</td>
</tr>
<tr>
<td>Section 34</td>
<td>M &gt; I</td>
<td>no</td>
<td>bornite, pyrite, sphalerite</td>
<td>no</td>
<td>peridotite, pyroxenite</td>
<td>anorthosite</td>
<td></td>
</tr>
<tr>
<td>Boulder Creek</td>
<td>M &gt; I</td>
<td>common</td>
<td>bornite, sphalerite</td>
<td>no</td>
<td>peridotite</td>
<td>troctolite</td>
<td></td>
</tr>
<tr>
<td>Boulder Lake North</td>
<td>M &gt; I</td>
<td>no</td>
<td>common</td>
<td>bornite, sphalerite</td>
<td>no</td>
<td>peridotite, pyroxenite</td>
<td>ferrogabbro, troctolite, anorthosite</td>
</tr>
<tr>
<td>Boulder Lake South</td>
<td>I &gt; M</td>
<td>yes</td>
<td>common</td>
<td>bornite, sphalerite</td>
<td>no</td>
<td>peridotite, pyroxenite</td>
<td>troctolite, basalt</td>
</tr>
</tbody>
</table>

*prmz is the Partridge River intrusion marginal zone; unit numbers correspond to Chapter 6, Figure 6.10.

Chandler and Ferderer, 1989; Chandler, 1990). The position of these oxide ultramafic intrusions relative to the magnetic high suggests that they may have also formed by a mechanism of intrusion and assimilation of the iron-formation (Severson, 1995). There are two potential problems concerning an origin that involves assimilated Biwabik Iron Formation. First, the high TiO₂ content of the oxide ultramafic intrusions is difficult to reconcile because the iron-formation contains only 0.03 to 0.19 percent TiO₂ (Morey, 1992). Muhich (1993) documented elevated TiO₂ contents (up to 6.0 percent in magnetic concentrates produced from taconite) at Dunka Pit where the iron-formation is in direct contact with the Duluth Complex. He suggested that the titanium was metasomatically transferred across the contact from the intruding silicate magmas. However, the titanium content in this example is still much lower than TiO₂ concentrations in the oxide ultramafic intrusions. The second problem is if the iron-formation is a potential source, it is difficult to reconcile how a dense, iron-rich, partial melt could have been forced upward along a fault. The dynamics involved in regard to the second problem have not been investigated. Miner (1995)
offered an alternative explanation for the origin of the Longnose oxide ultramafic intrusion that involves formation of a magmatic iron-rich melt along a fault to form a pipe-like body that was further modified by localized metasomatic replacement. Clearly, additional work is needed to further understand the origin of the N-OUI group.

The S-OUI group is not related to iron-formation assimilation because pelitic rocks of the Thomson Formation, rather than iron-formation, are present at the basal contact. These oxide ultramafic intrusions may be related to ferrogabbroic cumulates that are present above or at the same stratigraphic level. The S-OUI group may have formed by development of an iron-rich residual melt at the top of a crystallizing cumulate pile that drained down into the pile along faults (Severson, 1995). A similar origin of metasomatic replacement in response to downward percolating, iron-rich residual melts has been presented for iron-rich pegmatites in the Bushveld Complex of South Africa (Scoon and Mitchell, 1994).

In the above discussion on the origin of the oxide ultramafic intrusions, there is an obvious dichotomy regarding the relative movement of oxide ultramafic intrusion magma—upward in one case and downward in the other case. At present, there are no reliable indicators regarding the potential direction that the magma migrated. The same dichotomy applies to similar bodies in the Bushveld Complex. Stumpfl and Rucklidge (1982) suggested the bodies formed by the upward movement of magma, and Scoon and Mitchell (1994) envisioned formation from the downward movement of an iron-rich melt.

FISSURE VEIN POTENTIAL—LOGAN SILLS

Several types of fissure vein deposits that contain lead, zinc, copper, and silver minerals are known to occur across the Canadian border in the Thunder Bay district of Ontario. There, the deposits are associated with veins and fractures that crosscut rocks of the Animikie Group (Rove Formation and Gunflint Iron Formation) and Logan sills (Mudrey and Morey, 1972). The Thunder Bay district was first discovered in 1846 and sporadically produced almost $5,000,000 worth of silver ore prior to 1900 (Mudrey and Morey, 1972). Similar deposits have been searched for in Cook County, Minnesota, but none have proved to be commercial.

Along the Gunflint Trail in Minnesota, small sulfide veins with significant copper and cobalt values were reported at the Blankenburg–Whiteside prospect on the south shore of Loon Lake (T. 65 N., R. 3 W., sec. 34). The mineralized veins, which contain abundant arsenopyrite, occur at the base of the Logan sill (unit lsb, M-119) near its contact with the Rove Formation. Reports by Hubert (1954), Engen (1968), Johnson (1968), and Coyner (1974) stated that in the early 1930s, a prospector first brought the mineralization to the attention of lodge-owner R. Blankenburg. The mineralization was evident at the base of a cliff and Blankenburg dug several test pits attempting to trace the mineralization. At the cliff locale, where an adit was dug, the mineralization consists of branching arsenopyrite-quartz veins that contain abundant chalcopyrite and lesser amounts of pyrrhotite, magnetite, ilmenite, and hematite. The veins, as thick as several centimeters, strike approximately east–west and dip steeply to the south. There appear to be no sulfide veins higher than 9 meters above the base of the cliff.

Prospecting was eventually discontinued and did not resume until the 1950s when Blankenburg and R. Whiteside of Duluth conducted a drilling program of eight holes. Two holes struck arsenopyrite veins as wide as 5 centimeters and returned assays as much as 6.48 percent cobalt (Johnson, 1968). No core or drill logs are preserved from this early period of drilling. A second drilling program was undertaken between 1967 and 1971. Eighteen holes were drilled, the core of which is stored at the Minnesota Department of Natural Resources. Coyner (1974) suggested that the mineralization is associated with an east–west-trending monoclinal hinge line where the dip of both the Rove Formation and Logan sill increases from 25° to 65° to the south. Coyner (1974) reported grab samples that assayed 5.04 percent copper and 1.08 percent cobalt. Johnson (1968) reported values as high as 10.28 percent copper, 3.86 percent cobalt, and 1.51-ounce/ton silver.

A prospect on Susie Island in Lake Superior, south of Pigeon Point, consists of veins in a Grand Portage diabase dike (unit gpdb, M-119). The veins contain calcite and barite with minute inclusions of chalcocite and bornite, and lesser amounts of pyrite, chalcopyrite, and covellite (Mudrey and Morey, 1972). High-grade grab samples assayed as much as 6.22 percent copper (Grout and Schwartz, 1933). The Green prospect near Mineral Center, Minnesota (T. 63 N., R. 5 E.) is a vein
deposit localized within fractured, brecciated, and altered rocks of the Pigeon River diabase (unit prdb, M-119). Primary sulfides in the veins are pentlandite, pyrrhotite, and chalcopyrite (Schwartz, 1924, 1925). A sulfide concentrate from the Green prospect assayed 18.26 percent copper and 0.52 percent nickel (Mudrey, 1972).

**ECONOMIC SIGNIFICANCE OF THE NORTH SHORE VOLCANIC GROUP AND RELATED HYPABYSSAL INTRUSIONS**

At present, the only economic use of the volcanic and hypabyssal rocks along the north shore is as industrial quarry rock. One large, traprock quarry is operating in the Ely’s Peak basalts southwest of Duluth, but there is considerable potential for other such developments in the area, assuming a favorable market, economical transportation, and other factors. A quarry in the southeast side of Carlton Peak near Tofte is now inactive; it exploited the massive, widely-jointed anorthosite xenoliths contained in diabase for use as riprap. Large blocks of diabase removed from State Highway 61 tunnels northeast of Two Harbors are stockpiled at Castle Danger and are used as riprap for occasional erosion-control projects in the area. Anorthosite in the Beaver Bay Complex was briefly quarried in several places near the shore of Lake Superior early in the 1900s in the mistaken belief that it was corundum (Grout and Schwartz, 1939). The area was extensively explored for metallic deposits, especially copper, in the late nineteenth and early twentieth centuries (Green, 1972), but no viable deposits have been found.

The felsic rocks, both rhyolites and granophyres, might have some potential for hosting a number of metals of interest, such as base metals (including copper, zinc, or tin), precious metals (silver or gold), rare earth elements, tungsten, and uranium. A geochemical survey (Green, 1989) of felsic samples showed generally low values of these and other indicator elements (Table 8.3). However, there were a few more elevated values (greater than ten times the mean) for arsenic, gold, and tungsten, and one each for copper and zinc. Most of the material available for sampling (in outcrop) is relatively unaltered, whereas mineralization is more likely to be found in hydrothermally altered rocks such as permeable zones in flowtop breccias, tuffs, or shear zones. Such altered rocks, unless silicified, are typically more susceptible to erosion, and in this terrane are generally covered by glacial drift. An attempt was made to sample and analyze as many of these as feasible (where exposed in streambeds, shore cliffs, or road cuts), but most are inaccessible. In order to fully investigate the economic potential of these felsic rocks, it would be useful to conduct soil, stream sediment, or drift geochemical surveys, and a drilling/sampling program to investigate the

### Table 8.3. Selected trace-element values of economic interest in Keweenawan felsic rocks. Values in parts per million except for Au (parts per billion).

<table>
<thead>
<tr>
<th>Element</th>
<th>As</th>
<th>Sb</th>
<th>Au</th>
<th>Ag</th>
<th>Cu</th>
<th>Zn</th>
<th>Mo</th>
<th>U</th>
<th>W</th>
<th>Sn</th>
<th>Ce</th>
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<tr>
<td>Number of analyses</td>
<td>73</td>
<td>64</td>
<td>80</td>
<td>72</td>
<td>76</td>
<td>73</td>
<td>77</td>
<td>77</td>
<td>90</td>
<td>36</td>
<td>76</td>
</tr>
<tr>
<td>Number above detection limit</td>
<td>58</td>
<td>58</td>
<td>37</td>
<td>19</td>
<td>73</td>
<td>73</td>
<td>13</td>
<td>77</td>
<td>56</td>
<td>28</td>
<td>76</td>
</tr>
<tr>
<td>Detection limit(s)</td>
<td>1,2</td>
<td>0.1,0.2</td>
<td>2,10</td>
<td>0.5</td>
<td>1</td>
<td>0.5</td>
<td>2</td>
<td>0.1</td>
<td>1</td>
<td>2.3</td>
<td>1</td>
</tr>
<tr>
<td>Average, at or above detection limit</td>
<td>12.3</td>
<td>0.50</td>
<td>28</td>
<td>0.85</td>
<td>41</td>
<td>135</td>
<td>4.2</td>
<td>3.6</td>
<td>6.05</td>
<td>10.8</td>
<td>175</td>
</tr>
<tr>
<td>Average, all analyses*</td>
<td>9.8</td>
<td>0.46</td>
<td>13</td>
<td>0.24</td>
<td>40</td>
<td>135</td>
<td>0.7</td>
<td>3.6</td>
<td>3.8</td>
<td>8.4</td>
<td>175</td>
</tr>
<tr>
<td>Five highest values</td>
<td>110</td>
<td>1.7</td>
<td>170</td>
<td>1.5</td>
<td>430</td>
<td>1400</td>
<td>13</td>
<td>10.4</td>
<td>210</td>
<td>39</td>
<td>470</td>
</tr>
<tr>
<td>100</td>
<td>1.5</td>
<td>130</td>
<td>1.5</td>
<td>226</td>
<td>290</td>
<td>7</td>
<td>8</td>
<td>42</td>
<td>25</td>
<td>448</td>
<td></td>
</tr>
<tr>
<td>62</td>
<td>1.4</td>
<td>110</td>
<td>1.5</td>
<td>210</td>
<td>250</td>
<td>6</td>
<td>7</td>
<td>7</td>
<td>22</td>
<td>290</td>
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<tr>
<td>51</td>
<td>1.4</td>
<td>110</td>
<td>1.5</td>
<td>160</td>
<td>240</td>
<td>5</td>
<td>7</td>
<td>3</td>
<td>21</td>
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<tr>
<td>43</td>
<td>1.0</td>
<td>95</td>
<td>1.0</td>
<td>120</td>
<td>210</td>
<td>3</td>
<td>6.8</td>
<td>3</td>
<td>20</td>
<td>256</td>
<td></td>
</tr>
</tbody>
</table>

* Values below detection limit counted as 0
typically unexposed top zones of the large felsic volcanic flows.

The mafic rocks (basalt, diabase) also have economic significance as potential indicators of metal concentrations in associated intrusions. This results from the conditions associated with the separation of immiscible sulfide liquid from the mafic magma during crystallization. This can happen during closed-system crystallization, when the time of sulfide separation would be relatively late because of the generally low sulfur content of tholeiitic magmas; it can be promoted by assimilation of sulfur from adjacent country rocks; or it can be triggered by the assimilation of more siliceous wallrock, changing the liquidus relations (Irvine, 1975). Such a silicate liquid would tend to scavenge chalcophile elements, such as the base metals, from the magma. Thus nickel, which without a sulfide liquid present would be fractionated into olivine, would be depleted from the magma along with copper. This relationship presents a tool for regional exploration for sulfide or PGE ores (Lightfoot and others, 1997). If basaltic or diabasic rocks are depleted in copper and nickel, this suggests that somewhere in comagmatic plutonic intrusions there may be a concentrated sulfide deposit. This is well illustrated by the Noril’sk copper-nickel-PGE district associated with the Siberian Traps (Lightfoot and others, 1994).

Alternatively, if the basalts have “normal” elevated values of these chalcophile elements, it suggests that no sulfide separation and scavenging have taken place. Isotopic or other geochemical evidence for crustal contamination can also be used to infer the potential for sulfide exsolution by that mechanism (Lightfoot and others, 1997).

To evaluate this relationship for the North Shore area, nickel values were compared with MgO for 65 mafic dikes and mafic volcanic rocks of the North Shore Volcanic Group (Fig. 8.14). For the dikes, there is a clear positive correlation between nickel and MgO, with nickel values in the most magnesian dikes reaching 250 parts per million (Fig. 8.14a). Copper values are also high, with an average of 233 parts per million for the 42 samples with copper data. These imply that little scavenging has taken place, and the nickel is contained principally in the olivine. Brannon (1984) produced a consistent set of analyses of North Shore Volcanic Group lavas for a 4-kilometer section between Duluth and Two Harbors. Her 51 basaltic analyses also showed a strong positive correlation between nickel and MgO (Fig. 8.14b); no sample contained less than 62 parts per million nickel. No copper data for these flows are available. Fifty-four other basaltic North Shore Volcanic Group analyses contain data for nickel, 27 for the northeast limb and 27 for the southwest

![Figure 8.14](image-url)

**Figure 8.14.** A. Variation in nickel and MgO in diabase dikes (Green, 1986, unpub. data). B. Variation in nickel and MgO in North Shore Volcanic Group basaltic rocks from the upper southwest sequence (Brannon, 1984) and various North Shore Volcanic Group basaltic rocks from the northeast and southwest sequences (Green, 1986; unpub. data).
limb. Both sets again show a "normal," non-depleted trend of nickel and MgO; they are combined in Fig. 8.14b. A comparison of normal versus reversed magnetic polarity shows no significant difference in the MgO/nickel relationship. An average of 152 parts per million copper was found for the 17 analyses available.

These data imply that the magma sources that supplied these lavas and associated dikes experienced "normal," olivine-controlled fractionation without appreciable scavenging by immiscible sulfide liquids at depth. This conclusion is supported by the available lead, rubidium/strontium, and Sm/Nd isotope data for the basalts that indicate that little, if any crustal assimilation has affected these mafic liquids (Green, 1983; Dosso, 1984; Nicholson and others, 1997). It should be noted that the samples for these analyses were mostly collected in the general north shore area, although some came from inland localities. These are nearly all tens of kilometers from exposed plutons of the Duluth Complex, and may not have been connected to the intrusions of interest. Thus, it is not known how applicable these geochemical relations are to metallic exploration in the complex itself.

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