FIELD TRIP 4

GEOLOGY OF THE NICKEL LAKE MACRODIKE AND ITS ASSOCIATION WITH CU-NI-PGE MINERALIZATION IN THE NORTHERN SOUTH KAWISHIWI INTRUSION, DULUTH COMPLEX, NORTHEASTERN MINNESOTA

By

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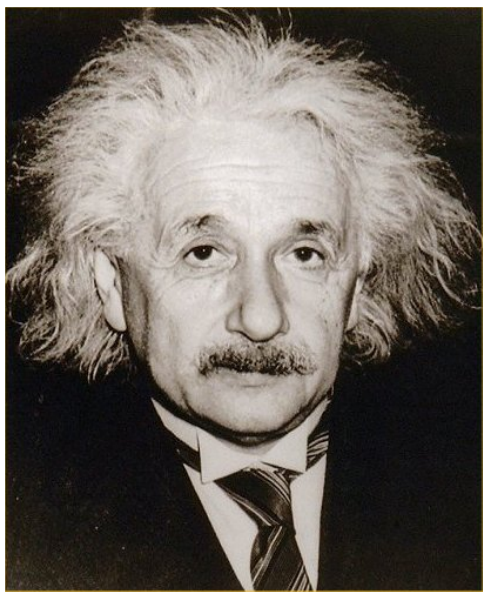

"Imagination is more important than knowledge"

Albert Einstein

INTRODUCTION

Mineral deposits are concentrations of specific ore-minerals that society utilizes in immeasurable ways. They have formed from Archean times up to the present, and vary greatly in commodity, mineralogy, alteration, trace element signature, geophysical properties, and grade-tonnage. Individual ore deposits are always unique, and this uniqueness arises from two main sources: 1) fundamental differences in geologic processes and environments; and 2) local, site-specific, geologic variations and associated bounding geometries. The seemingly limitless number of permutations of these (and other) features of mineral deposits defies imagination. Geologists employed in the search for ore deposits have, over the last century, developed the intellectual concept of **Ore Deposit Models**, which seek to organize many of these variables, lump individual mineral deposits into classes, and establish criteria to aid in mineral exploration (Peterson, 2001a). Such models may be strictly *empirical* – a collection of observable facts associated with the occurrence of certain metals in economic proportions – or *genetic* – which attempts to describe the physical and chemical processes responsible for the development of an ore deposit and its related empirical features.

Advances in our collective understanding of ore deposit types is nonlinear, rather it occurs in fits and starts. Take, for example, the great advance in knowledge – and thus mineral exploration models and exploration success – for porphyry copper deposits in the 1960s and 1970s (Lowell and Guilbert, 1970), volcanogenic massive sulfide deposits in the 1970s and 1980s (Franklin et al., 1981), and mesothermal lode gold deposits in the 1980s and 1990s (Hodgson, 1993). These advances were the product of many factors, which conceivably the most important was collaborative ore deposit research between the mineral industry, academia, government agencies, and research organizations.

We are currently in the midst of a similar great advance in knowledge of magmatic Ni-Cu-PGE deposits (Arndt et al., 2006; Barnes and Lightfoot, 2006; Eckstrand and Hulbert, in prep.). Perhaps the most important impetus for this current revolution was the fall of the Iron Curtain, which opened the door in the early 1990s to some of the world's greatest magmatic Ni-Cu-PGE deposits, i.e., the Noril'sk-Talnakh deposits in Russia and Jinchuan deposit in China, to economic geologists trained in open western societies (especially Canada). In addition, the 1993 discovery of the magmatic Ni-Cu deposit at Voisey's Bay, Labrador, Canada, and its inferred origin as a magmatic feeder dike, has brought about a revolution in our collective understanding of the origin of magmatic Ni-Cu±PGE deposits. This revolution can simple be stated as ***"find the magmatic feeder dike and/or channelized magma flow zones"*** to the ore-bearing mafic/ultramafic intrusion(s). A magmatic conduit that experienced repeated influxes of magma appears to be the key to the formation of high-grade, world-class, Ni-Cu-PGE deposits (Naldrett, 1997).

This field trip is truly the result of over two decades of dedicated Duluth Complex research, almost entirely funded by the State of Minnesota and the University of Minnesota, by geologists of the University of Minnesota Duluth's (UMD), Natural Resources Research Institute (NRRI). Steve Hauck, director of the NRRI's Economic Geology Group (EGG), is here thanked for his decades of dedicated research and seeing through that the EGG remains financially solvent through a never-ending series of budgetary crises. As well, the NRRI's Mark Severson – who has logged well over 900,000 feet of Duluth Complex drill core – has without a doubt the more knowledge than anyone on the geology of the mineralized zones within the deposits of the Duluth Complex. The authors of this guidebook have simply built upon this intellectual capital in new ways, including geochemical and 3-D modeling of drill core data, and especially the most basic geologic endeavor, detailed field mapping.

FIELD TRIP TENETS

Many basic attributes of the Duluth Complex Cu-Ni-PGE sulfide deposits resemble those of deposits at Noril'sk, Russia, Jinchuan, China, and Voisey's Bay, Canada that are associated with sulfide mineralization in intrusive feeder zones. Such attributes include shallow tholeiitic intrusions associated with plateau basalt volcanism, external sedimentary sources of sulfur, and openness to repeated magma influx and expulsion. However, the biggest difference between these world-class magmatic ore systems and the deposits of the Duluth Complex is the lack of significant nickel-rich (Ni>Cu) massive sulfide orebodies at Duluth. A critical attribute of the high-grade Noril'sk–Talnakh and Voisey's Bay deposits, not **previously positively identified** in the Duluth Complex, is the location of a magmatic conduit, i.e., the feeder zone.

Several geologists have previously identified possible conduits that may have fed the Partridge River (PRI) and South Kawishiwi (SKI) intrusions of the Duluth Complex. Severson and Zanko (unpub. data) suggest that the Grano fault might mark a possible feeder zone for the Local Boy ore zone at the northeast end of the PRI. Thériault et al. (2000) postulated that a PRI conduit was present somewhere between the

Wetlegs and Dunka Road deposits. Another possible PRI 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 sub-vertical magmatic feeder beneath the Bald Eagle intrusion (BEI) based on field relations (Weiblen and Morey, 1980) and geophysical attributes (Chandler, 1990).

Peterson (2001b) interpreted the systematic variation in Cu-Ni-PGE mineralization in the Maturi deposit and its extension east to Maturi Extension, as indicative of magma input from the east-northeast via an arcing macrodike (herein first termed the Nickel Lake Macrodike (NLM)) that connects the deep-seated source of the BEI and the SKI. Subsequent mapping and research (Peterson, 2002a-f, 2006a, Peterson et al., 2004, Peterson and Hauck, 2005) has built on this model, which recently culminated with the publication of a new detailed bedrock geology map of the area (Peterson et al., 2006). If correct, this model predicts that a Voisey's Bay-type Ni-Cu-PGE massive sulfide body may exist at depth in the area where the NLM meets the SKI, south-southeast of the Spruce Road deposit (see Figs. 4.2 and 4.3). This field trip will investigate evidence that the NLM is a feeder to the SKI, and thus is one of the principal conduits (only?) that brought Cu-Ni-PGE from the Earth's mantle and/or lower crustal magmatic staging chambers into the Earth's upper crust via the NLM into the SKI. This will be accomplished through scientific discussions (hopefully heated) on numerous outcrops (Day 1) as well as visualization of the geology in 3-D and displays of recently drilled cores by Duluth Metals Limited (Day 2).

The fundamental tenet of this field trip is to convey to the participants the notion that science gives one the ability to **imagine reality.** Herein, *science* is geologic research of the Duluth Complex (geologic mapping, drill core logging, geochemical studies, and exploration drilling), and *reality* is new understanding how this magmatic system concentrated and enriched known and potential concentrations of Ni-Cu-PGE at the base of the NLM in the field trip locale as well as adjacent areas of the SKI. The field trip leaders ask the participants (and others who may use the guidebook in the future) to use their imaginations throughout the field trip (or subsequent field excursions) to think about a few basic known and possible realities of the Duluth Complex:

1) The Duluth Complex is perhaps the world's largest untapped resource of Ni-Cu-PGE, with multi-billion tons of geologic resources estimated to be worth >1 trillion dollars, (Peterson, 2006c);
2) The general geologic setting of the deposits in the Duluth Complex is similar to other world class Ni-Cu-PGE mining camps hosted by rocks in rift settings (Noril'sk-Talnakh, Jinchuan);
3) Overall, the ratio of Ni to Cu in Duluth Complex deposits average 1:3;
4) Worldwide, the ratio of Ni to Cu in similar deposits averages between 1:1 to 2:1;
5) By analogy, there seems to be an enormous mass of missing Ni-rich mineralization;
6) At depth, the Nickel Lake Macrodike may host a large percentage of this missing Ni in the SKI.

MAGMATIC NI-CU-PGE ORE DEPOSIT MODEL

The basic starting point to begin our quest to understand the significance (both geologic and economic) of the Nickel Lake Macrodike is a quick review of the magmatic Ni-Cu-PGE ore deposit model. There are literally hundreds of recent publications in the geological literature that deal with this important class of ore deposit, and readers interested in this topic may find that Barnes and Lightfoot (2006), Arndt et al. (2006), Eckstrand and Hulbert (in prep.), Naldrett, (1989, 1997, 1999), Naldrett et al. (2000), Li and Naldrett (1999), Lightfoot et al. (1994) and references therein are excellent reviews that describe magmatic Ni-Cu-PGE deposits in general, and major deposits in particular.

Magmatic Ni-Cu-PGE sulfide deposit occur as sulfide concentrations associated with a variety of mafic to ultramafic rocks in four major geological settings: 1) rifts and continental flood basalt settings (Noril'sk-Talnakh, Russia; Duluth Complex, Minnesota; Jinchuan, China); 2) meteorite impacts (Sudbury, Ontario, the only mining camp in this class); 3) komatiite lava flows and related intrusions (Thompson, Manitoba; Raglan, Québec; Kambalda, Australia; Pechenga, Russia); and 4) a variety of miscellaneous tholeiitic intrusions (Voisey's Bay, Labrador; Lynn Lake, Manitoba). The ores are enriched in sulfur, iron, nickel, copper, cobalt, and the platinum group elements (Pt, Pd, Rh, Ru, Ir, and Os) and may contain minor Ag, As, Au, Bi, Hg, Pb, Sb, Se, Te, and Zn. Grade-tonnage diagrams for magmatic Ni-Cu-PGE sulfide deposits/camps are presented in Figure 4.1 which highlights the major camps/deposits listed above.

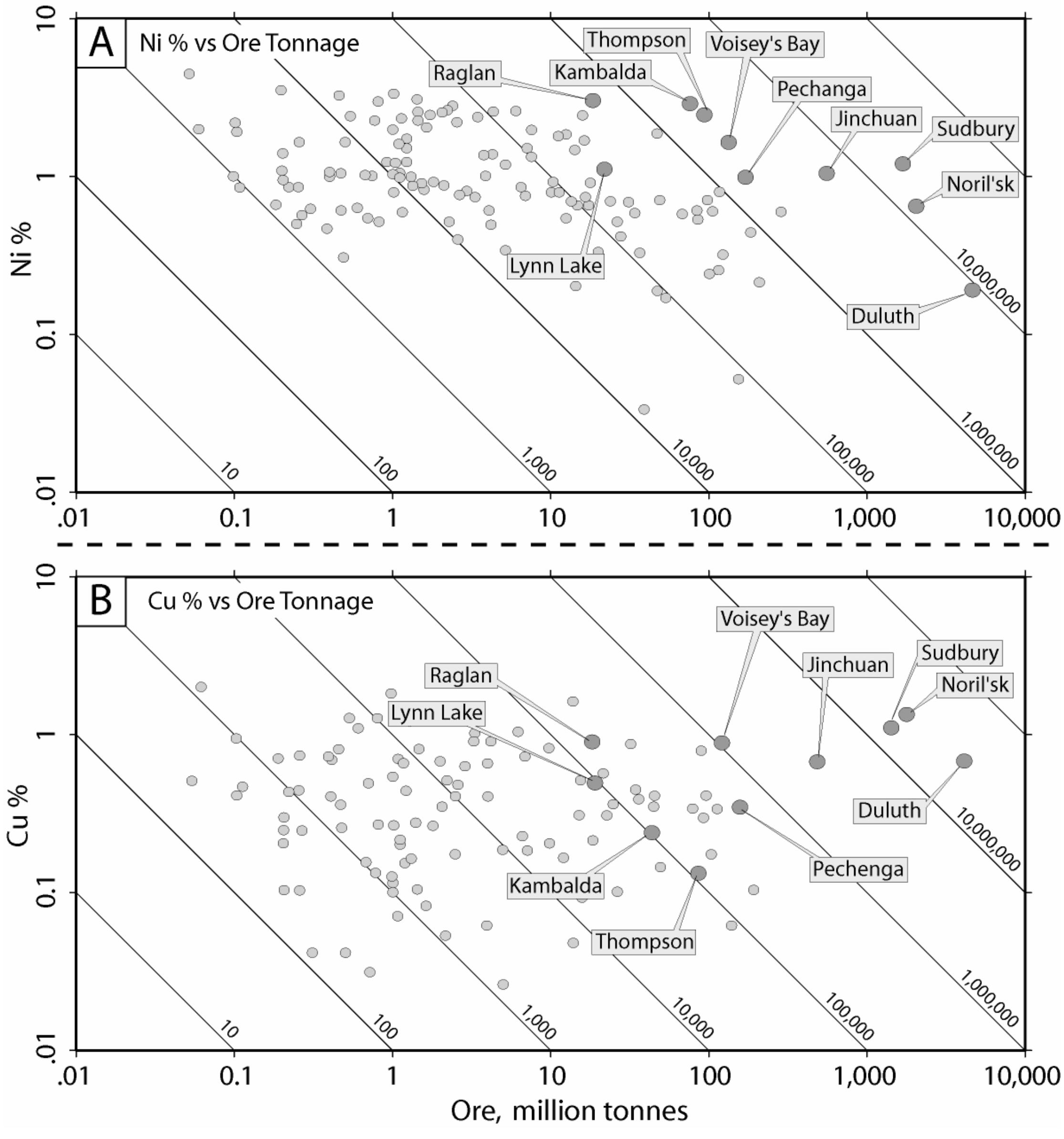

Figure 4.1. Tonnage and Ni grades of magmatic Ni-Cu sulfide deposits; B. Tonnages and Cu grades of magmatic Ni-Cu sulfide deposits. Inclined contours show quantities of contained metals (tonnes) in each figure. Figure modified from Eckstrand and Hulbert, in prep.

The basic intrinsic geological features characteristic of a vast majority of magmatic Ni-Cu-PGE sulfide deposits include: (1) olivine-rich magmas; (2) proximity to a major crustal fault; (3) sulfide-bearing country rocks; (4) chalcophile element depletion in related intrusive or extrusive rocks; (5) field and/or geochemical evidence of interaction between the magma and the country rocks; and (6) presence of, or proximity to, a magma conduit (Naldrett, 1999). Fundamental geologic processes and constraints that together leads to the formation of these deposits include:

1) Deposits form as the result of segregation and concentration of droplets of liquid sulfide from mafic or ultramafic magmas;
2) Chalcophile elements from the silicate melt partition into the droplets as a result of turbulent magma flow;
3) An appropriate physical environment is required so that the sulfide liquid mixes with enough magma to become adequately enriched in chalcophile metals;
4) Sulfides must cluster in a restricted locality, generally due to the influence of gravity, so that the resulting metal concentration is of ore grade;
5) Massive sulfide concentrations form a high-temperature monosulfide <u>solid</u> solution (MSS);
6) As the MSS cools, it exsolves minerals and fractionates;
    a. Forms a solid cumulate mass of pyrrhotite-rich massive sulfide (enriched in Fe, Ni, Co, Ir, Ru, Rh).
    b. Forms a liquid residuum that is enriched in Cu, Pd, Pt, Au, and other minor elements, including As, Bi, Te, Sb (which will crystallize later into minerals as the system cools).
7) For some time, the Cu-Pd-Pt residual liquid can move and form high grade ore shoots/deposits
    a. i.e., footwall veins in Sudbury can be 30 wt. % Cu and multi-ounce/ton Pt + Pd.

Possibly the greatest recent advance in understanding Ni-Cu-PGE sulfide deposits has been the appreciation of coherent and compelling scientific arguments that have shown that magma dynamics play a key role in the concentration and metal enrichment of sulfide minerals in these deposits (Naldrett, 1997). These arguments build on the long held notion that sulfide-rich orebodies achieve their concentrations mainly through the settling of sulfide droplets in magmas due to the effects of gravity. The new fundamental tenet has been the realization that **decreases in the flow rate of magmas**, principally due to the geometry and obstructions in magmatic conduits, is the major factor in settling entrained sulfide droplets and forming sulfide-rich orebodies (Eckstrand and Hulbert, in prep.). These geometries include, for example, widened parts of magmatic feeder dikes, the lowest zones of undulating basal zones of conduits, and the location where such dikes enter larger magma chambers. Geologists that are engaged in Ni-Cu-PGE exploration projects should use their imaginations to envision magma dynamics like a person fly-fishing along a stream, and search for deposits behind the large boulders and in the slow-moving pools below rapids where the big rainbow and brown trout are most likely to be found.

REGIONAL GEOLOGIC SETTING, DULUTH COMPLEX

The Duluth Complex and associated intrusions of Keweenawan age (~1.1 billion) in northeastern Minnesota constitute one of the largest mafic intrusive complexes in the world, second only to the Bushveld Complex of South Africa (Miller et al., 2002). These rocks cover a 5,700 square kilometer arcuate area associated with the two strongest gravity anomalies (+50 and +70 milligals) in North America, that imply intrusive roots more than 13 kilometers deep (Allen and others, 1997). The comagmatic flood basalts and intrusive rocks underlying most of northeastern Minnesota were emplaced during the development of the Mesoproterozoic Midcontinent rift, which can be traced geophysically from exposures in the Lake Superior region along a 2,000 kilometer-long, segmented, arcuate path to Kansas and Lower Michigan. The Duluth Complex is defined as the more or less continuous mass of mafic to felsic plutonic rocks that extends for >275 kilometers in an arcuate fashion from Duluth nearly to

Grand Portage (Fig. 4.2). It is bounded by a footwall of Paleoproterozoic sedimentary rocks and Archean granite-greenstone terranes (Peterson and Severson, 2002), and a hanging wall largely of comagmatic, rift related flood basalts and hypabyssal intrusions of the Beaver Bay Complex (Fig. 4.2). In genetic terms, the Duluth Complex is composed of multiple discrete intrusions of mafic to felsic tholeiitic magmas that were episodically emplaced into the base of a comagmatic volcanic edifice between 1108 and 1098 Ma.

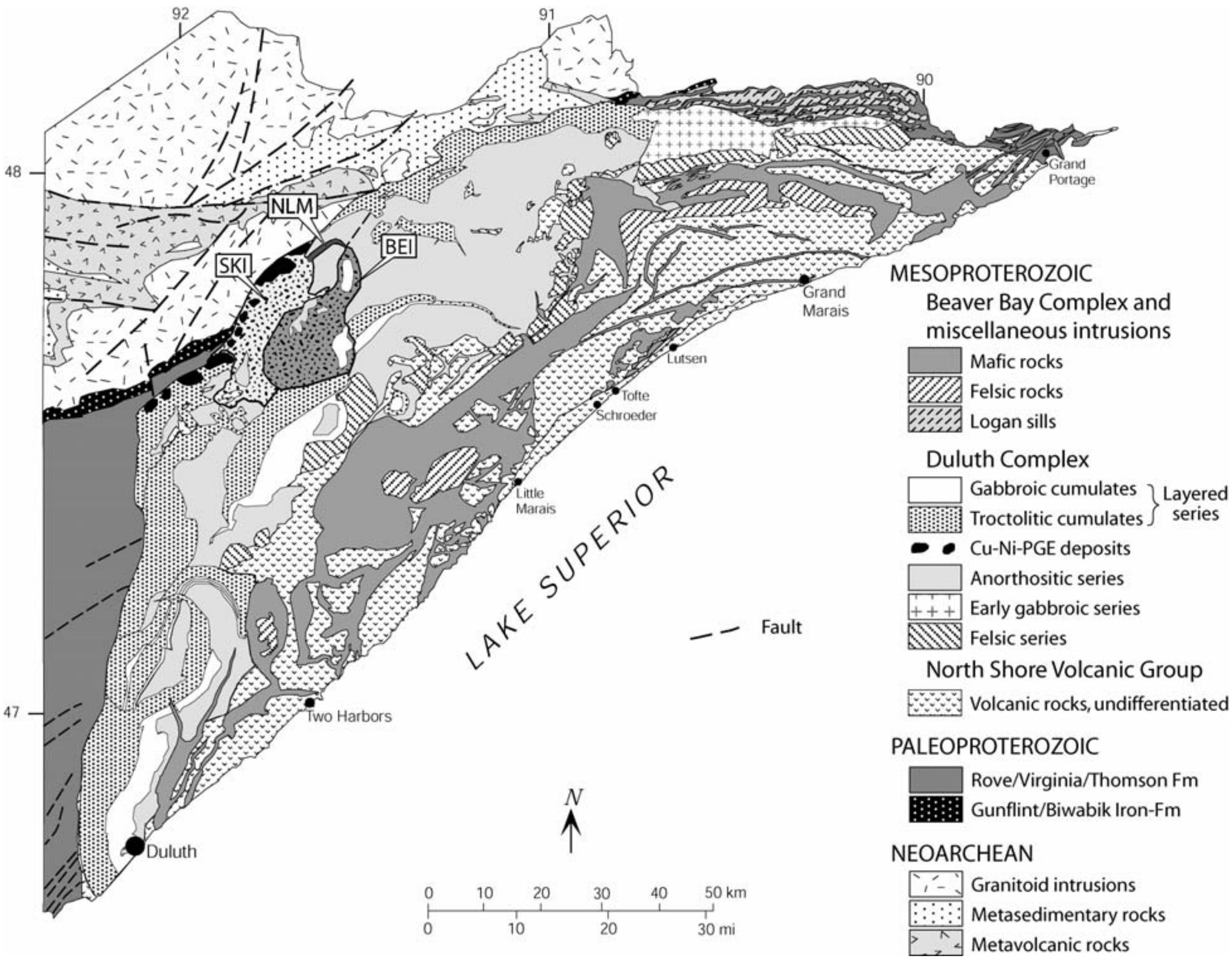

Figure 4.2. Generalized geologic map of northeastern Minnesota. Highlighted intrusions include the Bald Eagle (BEI) and South Kawishiwi (SKI) intrusions, as well as the linking Nickel Lake Macrodike (NLM) (modified from Miller et al., 2002).

The geology of the Duluth Complex and adjacent areas has recently been described in two major publications by the Minnesota Geological Survey (MGS). These include a 1:200,000 scale regional bedrock geological map of northeastern Minnesota (Miller et al., 2001), and a comprehensive written description of the geology depicted on this map (Miller et al, 2002), commonly referred to as the “bible” by geologists working on Duluth Complex geology. Readers’ interested in more detailed descriptions of the geologic setting of the Duluth Complex should begin their quest for knowledge by downloading these publications from the MGS website (ftp://mgssun6.mngs.umn.edu/pub2/). Within the nearly continuous mass of intrusive igneous rock forming the Duluth Complex, four general rock series are distinguished on the basis of age, dominant lithology, internal structure, and structural position within the complex.

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

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

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

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

This field trip will investigate rocks of the Layered Series – the SKI, NLM, and by implication the BEI – and Anorthositic series rocks in outcrops within and along the margins of the NLM. It is hoped that discussions on the outcrop (Day 1), coupled with examinations of selected sections of mineralized Duluth Metals Limited drill core from the SKI, and visualization of the geology in a 3-D presentation (Day 2) will bring new insight to the geology and mineral potential of the field trip area to the participants. Prior to these investigations, the quick descriptions of the local geology, basal contact-associated styles of Cu-Ni-PGE mineralization, and calculated Cu-Ni grade-tonnage geologic resources within this area that follow will give the field trip participants a better appreciation of the significance of the NLM and its inferred potential for hosting great quantities of Ni-rich sulfide mineralization at depth.

LOCAL GEOLOGIC SETTING

Robust field and geophysical data suggest that the emplacements of the BEI and SKI may be closely linked (Weiblen and Morey, 1980). At the northern margin of the BEI, a macrodike of well-foliated troctolite (herein termed NLM) arcs northwest to southwest and merges with the middle of the northern SKI (Fig. 4.3). Green et al., (1966) mapped the macrodike as part of the SKI, but its composition is very similar to the troctolitic phase of the BEI. Peterson (2001b) proposed a model for the mineralization in the SKI whereby the initial emplacement of the intrusion was formed by sulfide-contaminated magmas that emerged from the NLM and flowed southwest between a footwall of Archean granite and a hanging wall of Anorthositic series rocks. Miller et al. (2002) present an important interpretive model for the emplacement of the BEI and SKI via a common feeder system, as well as depict the origin of sulfur saturation of basal SKI magmas (Fig. 4.4) due to contamination from Paleoproterozoic sedimentary rocks (Ripley, 1986). Peterson et al. (2006) completed detailed geological mapping along the western end of the NLM and adjacent SKI, and have defined distinct mappable units in both of these troctolitic bodies.

BALD EAGLE INTRUSION

The BEI is a large (4.5 to 16.5 km x 31 km) troctolitic to gabbroic body that was emplaced partially within Anorthositic series rocks, the SKI, and the Greenwood Lake Intrusion (Fig. 4.2). Weiblen (1965) mapped the well-exposed northern portion of the intrusion and showed that it consists of an outer zone of troctolite and an inner zone of olivine gabbro. In the poorly exposed southwestern portions of the intrusion, field mapping by Green et al., (1966) and Foose and Cooper (1978) showed the BEI and SKI in direct conformable contact. Steep foliation and modal layering (Weiblen, 1965; Green et al., 1966) integrated with a distinct gravity anomaly over the northern BEI imply that the northern part of this intrusion is funnel shaped and necks down to a steep feeder dike. Weiblen and Morey (1980) interpreted the limited cryptic variation (Weiblen, 1965), the steep dip of lamination and layering, and adcumulate nature of the BEI as indicative of its being an open conduit to higher intrusions and perhaps volcanic flows.

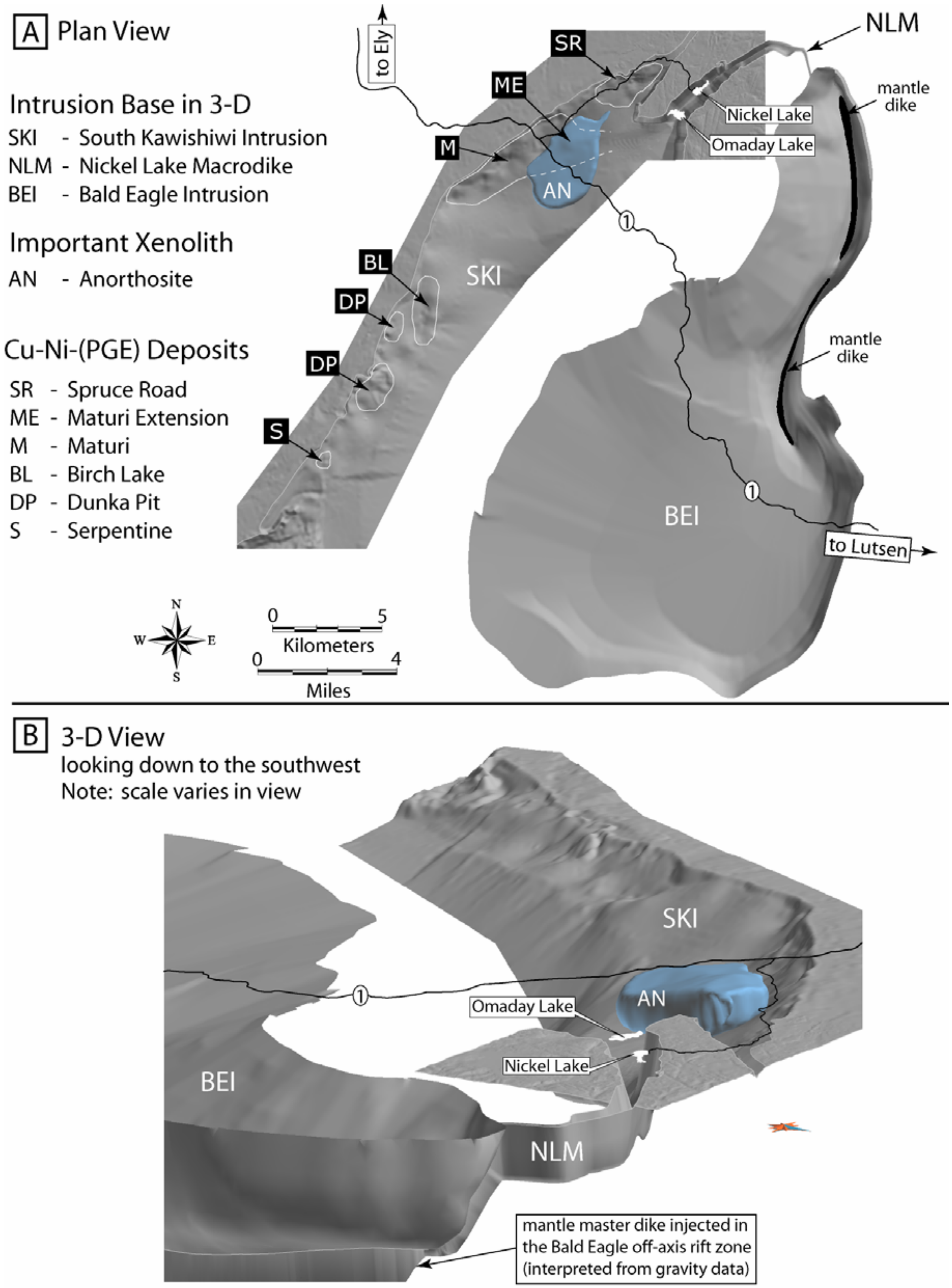

Figure 4.3. Simplified views of an integrated 3-D model of the BEI, NLM, and SKI of the Duluth Complex. A. plan view and B. view to the southwest. Model surfaces built from drill hole piercing points, detailed geological mapping, and interpretation of gravity and aeromagnetic data.

Petrologic observations and geophysical interpretations (Chandler, 1990; Chandler and Ferderer, 1989) suggest that the BEI and SKI were emplaced by successive overplating of magmas from a common feeder centered on the northern BEI and extending along the trace of the NLM that links the BEI and SKI. A model that depicts the origin of the BEI and SKI via a common dynamic feeder by Miller et al. (2002) is presented in Figure 4.4. In a related analogy, Cartwright and Møller-Hansen (2006) have shown that interconnected sill complexes transect the middle to upper crust over a vertical distance of 8-12 km offshore of Norway. The geometry of the gravity and magnetic anomalies of the BEI, as well as the overall Midcontinent Rift is very similar to the pattern of the seismic reflections profiles of active ridge systems (Vislova, 2003). In detail, the geophysical expressions of the BEI have the same shape and dimensions as the "bulls' eye" pattern of low velocity seismic reflection anomalies along the East Pacific Rise. These anomalies are interpreted to define regions of melt concentrations, i.e., active magma chambers. These data suggest that the BEI could be a "frozen" dynamic magma chamber (Weiblen et al., 2005; Peterson and Hauck, 2005).

The BEI has posed unresolved questions concerning its origin and magmatic significance since its discovery in 1961 (Weiblen, 1965, Weiblen and Morey, 1980, Miller et al., 2002). A number of its characteristics contrast markedly with those of the other mapped intrusions in the Midcontinent Rift: 1) it has a well-defined intrusive contact in Anorthositic series rocks around its northern perimeter; 2) there is a subtle, but recognizable metamorphic contact effect on these anorthositic gabbros; 3) a primary magmatic foliation is well defined by mineral orientation and discoid segregation of plagioclase from mafic phases; 4) foliation measurements define a steeply-dipping asymmetric funnel with the foliation paralleling the contact and grading from steep to horizontal inward; 5) the intrusion consists of two cumulus units, an outer troctolite and inner olivine gabbro; and 6) there is only minor (< a few %) intercumulus material in the cumulates, i.e., clinopyroxene and iron oxides (Weiblen et al., 2005).

SOUTH KAWISHIWI INTRUSION

The South Kawishiwi intrusion (SKI), together with the similar sized Partridge River intrusion (PRI) immediately to the south, are most renown for hosting the largest tonnage of Cu-Ni sulfide mineralization in the world (Naldrett, 1997). The realization that the SKI hosts vast quantities of Cu-Ni mineralization over 50 years ago has lead to the publication of numerous geologic maps, (Green et al., 1966; Bonnichsen, 1974; Foose and Cooper, 1974; Miller et al., 2001; Peterson, 2002e, f; Peterson et al., 2004; Peterson, 2006b; Peterson et al., 2006), articles (Bonnichsen et al., 1980; Weiblen and Morey, 1980; Ripley, 1986; Chandler and Ferderer, 1989; Lee and Ripley, 1996; Hauck et al., 1997; Peterson, 2001b) theses (Weiblen, 1965; Vislova, 2003; Marma, 2003), and reports (Phinney, 1969; Phinney, 1972; Listerude and Meineke, 1977, Morey and Cooper, 1977; Foose, 1984; Dahlberg, 1987; Dahlberg et al., 1989; Kuhns et al., 1990; Severson, 1994; Zanko et al., 1994; Hauck et al., 1997; Peterson, 1997; Peterson, 2001c; Miller et al., 2002; Peterson, 2002d; Patelke, 2003; Severson and Hauck, 2003).

The SKI is shallow dipping (~20º to the east-southeast) sill-like intrusion dominantly composed of troctolitic cumulates that are exposed in an 8- x 32-kilometer arcuate band along the northwestern margin of the Duluth Complex (Fig. 4.2). Footwall rocks include the Paleoproterozoic Virginia Formation in the Serpentine and Dunka Pit deposits, the Paleoproterozoic Biwabik Iron Formation in the Dunka Pit and Birch Lake deposits, and the Archean Giants Range batholith from the northern Birch Lake deposit north to the Spruce Road deposit (see Fig. 4.3 for deposit locations). The presence of shallow-dipping Biwabik Iron Formation inclusions as far north as the Spruce Road deposit indicates that the majority of Paleoproterozoic units were assimilated and removed from the footwall during emplacement of the SKI, leaving the Giants Range batholith as the dominant footwall rock type. Alternately, the Virginia and Biwabik Iron Formations may simply have been largely eroded prior to the development of the Mid Continent Rift. Also present as inclusions in the SKI are mafic volcanic hornfels (North Shore Volcanic Group), quartz sandstone hornfels (either the Puckwunge or Nopeming sandstones), and anorthosite (of the Anorthosite series). Anorthositic series rocks abut the SKI on the northeast – and enclose an interpreted SKI feeder dike (the NLM) that extends farther northeast – the PRI forms the southern sidewall of the SKI, and the BEI and Anorthositic series rocks overlie the SKI to the east (Fig. 4.2).

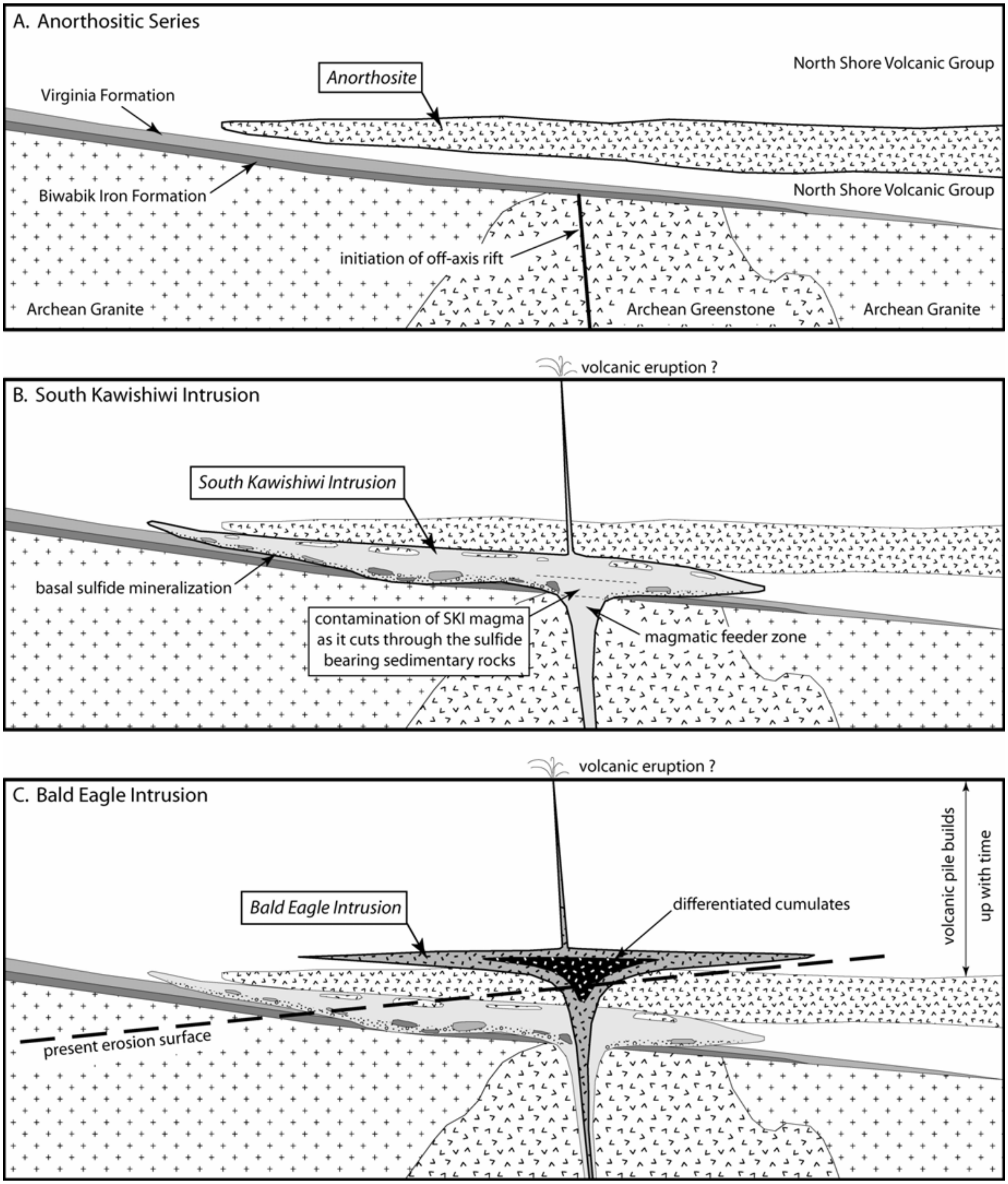

Figure 4.4. Interpretive model which depicts the emplacement and mineralization mechanisms of the South Kawishiwi and Bald Eagle intrusions via a common feeder system. A) Intrusion of plagioclase crystal mushes into volcanic rocks to create Anorthositic series rocks; B) Intrusion of the SKI below Anorthositic series rocks, with the early basal units reaching sulfur saturation via contamination from Paleoproterozoic sedimentary rocks; and C) Intrusion of the BEI above Anorthositic series rocks. Modified from figure 6.15 of Miller et al. (2002).

On the regional Duluth Complex map of Miller et al. (2001), the SKI is subdivided into five major map units. These are, from the base upward,

1. Heterogeneous **sulfide-bearing** troctolite, gabbro, and norite with localized hornfels inclusions;
2. A thick unit of subophitic to ophitic augite troctolite;
3. Discontinuous and localized layers of poikilitic leucotroctolite;
4. A thick homogeneous sequence of ophitic troctolite; and
5. A thick uppermost sequence of homogeneous troctolite that contains numerous anorthositic layers.

Severson (1994) and Zanko et al. (1994) further subdivided the SKI into 17 different lithostratigraphic units that are present in over 180 drill holes over a strike length of 31 kilometers. Sulfide mineralization is confined to the BH, BAN, UW, and U3 units near the base of the intrusion, and to a lesser extent the U1, U2, and PEG units. Major marker horizons that are correlated in drill holes include three horizons with abundant cyclic ultramafic layers (U1, U2, and U3 units) and a pegmatite-bearing unit (PEG unit) that was initially recognized by Foose (1984). The understanding of the significance of a large anorthositic inclusion (Fig. 4.3), originally intersected in six deep drill holes east of the Maturi deposit, and its role in magma dynamics of the SKI has been a key feature in the development of an exploration model for Duluth Metals Limited's Maturi Extension deposit (Peterson, 2001c).

Basal SKI Mineralization

Basal mineralization within the South Kawishiwi intrusion has traditionally been divided into five distinct deposits: 1) Serpentine, 2) Dunka Pit, 3) Birch Lake, 4) Maturi, and 5) Spruce Road. Recent drilling by Duluth Metals Limited has confirmed the existence on an additional economically significant deposit east of Maturi first envisioned by Peterson (2001c), named the Maturi Extension deposit (Fig. 4.3). Although the style of mineralization in all of the deposits is dominated by disseminated Cu-Ni sulfides, differences occur between the deposits in igneous stratigraphy, sulfide mineralogy, Cu-Ni and PGE grade, mineralization thickness, and contained tonnes. In addition to mineralization spatially associated with the base of the intrusion, a distinct zone of Cu and PGE-enriched mineralization occurs thousands of feet above the base of the intrusion within linear zones in the South Filson Creek deposit (Kuhns et al., 1990). Compilation and analysis of drill hole assay data by Peterson (2001, 2002a-d) has led to new understanding of two distinct styles of mineralization associated with the base of the SKI. These distinctive styles of mineralization are spatially coherent, i.e., the boundaries between them are linear (Fig. 4.5), and Peterson (2001b, c) informally termed them *open* and *confined*, which are described in more detail below.

"Open" - vertically extensive (can be > 450 meters) mineralization with low - high Cu-Ni grade and low Au+PGE grades. Cu-Ni grades commonly increase towards the basal contact although mineralized zones are typically erratic in their spatial extent and grade. Restricted zones of massive sulfide locally occur at, and/or immediately below, the basal contact. The erratic pattern of mineralization in part mirrors the lithologic heterogeneity of the basal units and may reflect repeated input of small pulses of barren and sulfur-contaminated magma. Examples of this "Open" style include the Spruce Road, Serpentine, and Dunka Pit deposits. The Serpentine deposit is unique within this group as it contains significant tonnage of pyrrhotite-rich massive sulfide at the basal contact that is associated with an immediate footwall sulfide source (Zanko et al., 1994).

"Confined" - vertically restricted (< 150 meters) mineralization with moderate - high Cu-Ni grades and moderate to very high (locally) Au+PGE grades. Cu-Ni grades typically are the highest near the top of the mineralized zone (upper BH into U3) and gradually decrease with depth toward the basal contact. Only limited zones of massive sulfide occurring at, and/or immediately below, the basal contact have been identified. For example, the upper portion of the mineralized zone within the Maturi deposit (which averages ~150 feet thick) commonly exhibits copper values nearing 1.0%

that decrease to ~0.25% at the basal contact. The spatial continuity of both the igneous stratigraphy and Cu-Ni-PGE grades of this style of mineralization point toward larger sustained inputs of magma (and/or more turbulent input of magma, thus higher fractionation of base- and precious-metals into the sulfide fraction) than the "Open" style. Examples of the "Confined" style include the Maturi, Maturi Extension, and the Birch Lake deposits.

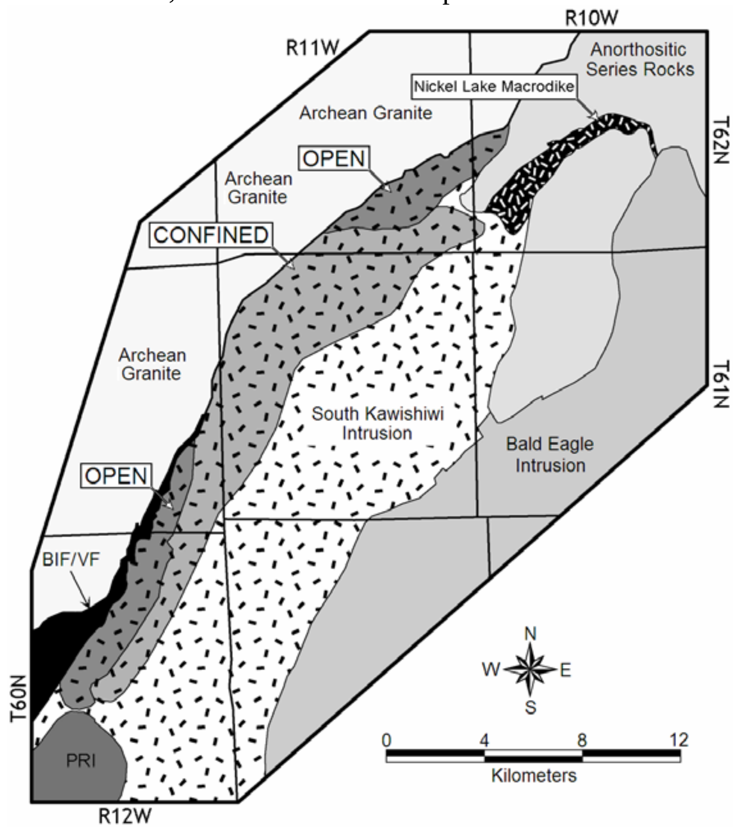

Figure 4.5. Location map of Open and Confined styles of mineralization in the South Kawishiwi Intrusion.

Recently completed (Peterson, 2002a, 2006a, b, c) and ongoing research on the distribution of Cu-Ni-PGE in the SKI integrates detailed geological mapping, drill hole logging, assay compilation, grade-tonnage calculation, recalculation of assay data to 100% sulfide, and 3-D visualization in order to imagine the coupled magmatic dynamics and mineralization history of the area. The most profound difference in the Open and Confined styles of Cu-Ni-(PGE) mineralization is perhaps best revealed in plots of assay data that have been recalculated to 100% sulfide compositions (Kerr, 2001, Naldrett et al., 2000). Such plots give one clues to the complicated history of immiscible sulfide droplets within SKI magmas, and could be used to calculate R-factors (herein the mass transfer of chalcophile elements between immiscible sulfide and silicate liquids in magmas) of the mineralization systems. As well, discrimination of different styles of mineralization and their internal metal budgets lets one come to grips with item 3 of the previously described Ni-Cu-PGE ore deposit model, that states, *"An appropriate physical environment is required so that the sulfide liquid mixes with enough magma to become adequately enriched in chalcophile metals"*. Geochemical plots of drill core assay data recalculated to 100% sulfide for the Open and Confined styles of mineralization are presented in Figure 4.6, and reveal profound differences in the metal budgets of the sulfide mineralization. Any genetic ore deposit model and/or mineral exploration model used to search for additional mineralization in the SKI must attempt to explain these differences in context with the overall NLM-SKI magmatic system, i.e. its timing, geometry, and magmatic plumbing.

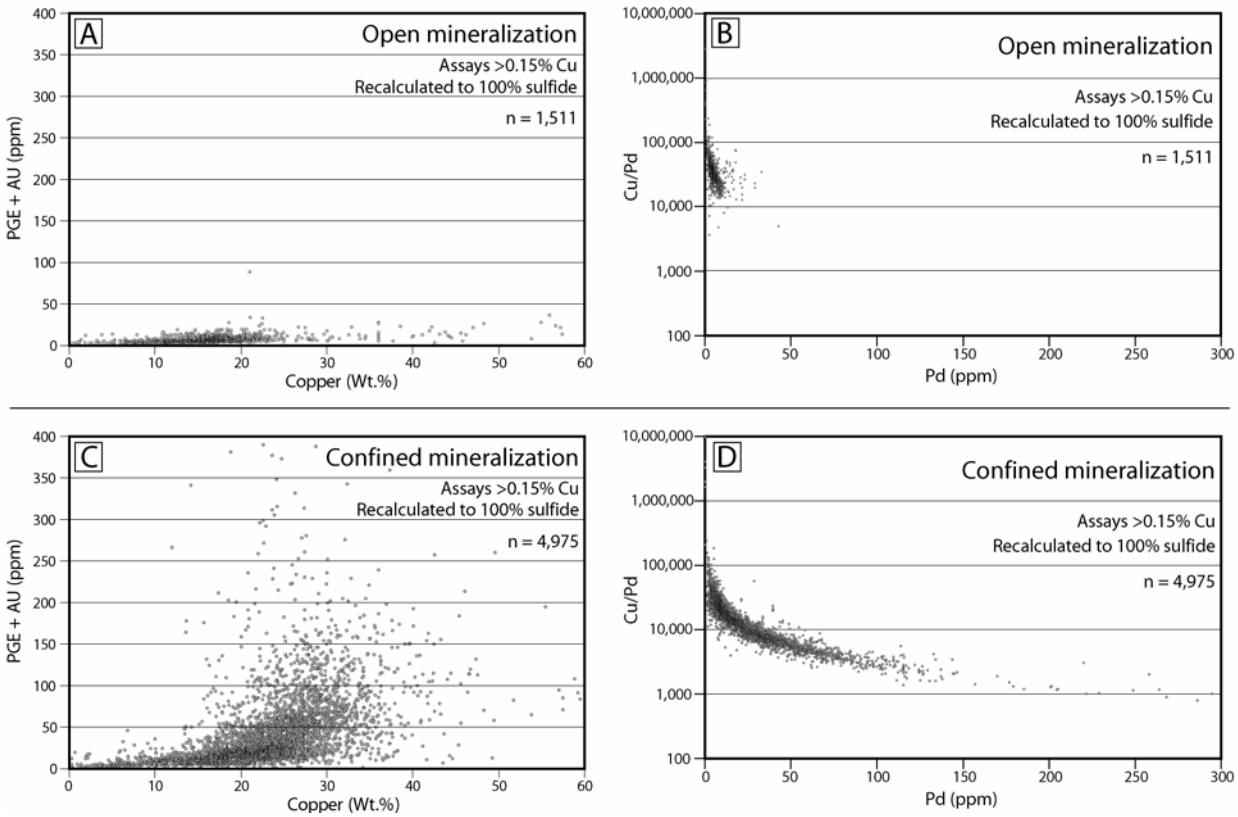

Figure 4.6. Geochemical plots utilizing recalculation of assay data to 100% sulfide (Kerr, 2001) to discriminate variations of metals in sulfide minerals in the two major styles of basal contact associated mineralization in the SKI. A) Open-style PGE+Au vs. Cu plot, B) Open Style Cu/Pd ratio vs. Pd plot, C) Confined-style PGE+Au vs. Cu plot, D) Confined-style Cu/Pd ratio vs. Pd plot.

Recent research in developing Cu and Ni grade maps (Peterson, 2002d) for deposits in the SKI, coupled with the realization that there are two distinct styles of basal-contact associated mineralization, has lead to the publication of inferred grade-tonnage estimates of Open and Confined styles of mineralization (Peterson, 2002c). Grade and tonnage data categorized into the Open and Confined styles of Cu-Ni mineralization within the South Kawishiwi intrusion are given in Table 4.1, which used all publicly available assay data in the year 2001. These mineral resource estimates have been calculated by the senior author (Peterson) following as much as possible the definitions and guidelines adopted by the Canadian Institute of Mining, Metallurgy, Petroleum (CIM "Standards on Mineral Resources and Reserves") in August 2000 (Postle et al.). Due to the fact that they rely on historic data from a variety of different sources, the level of data verification expected by the guidelines was not possible in all cases. Inherent uncertainties in the estimation and accuracy of these mineral resource estimates are a function of the quantity and quality of the available drill hole assay data and the quality of the methods used to determine them, which for the Spruce Road deposit are outlined in Peterson (2002d).

It is hoped that the data presented so far in this field guide, once integrated together in one's mind, leads to the conclusion that understanding the geologic history of the NLM may lead to profound advances in our understanding of Cu-Ni-PGE mineralization in the SKI. Such understanding may ultimately lead to the discovery of the *"Missing Nickel"* in the Duluth Complex Cu-Ni-PGE deposits, thus redefining the district as the Duluth Complex Ni-Cu-PGE deposits.

Table 4.1. Cumulative inferred mineral resource estimates for the Open and Confined styles of mineralization in the South Kawishiwi intrusion. Open style modeled to 1500 Ft. (457m.) and Confined style modeled to 500 Ft. (152m.) above base.

Copper Cutoff	Open Style Mineralization			Confined Style Mineralization		
	Cu %	Ni %	Tonnes	Cu %	Ni %	Tonnes
1.05	1.043	0.559	114,000	1.035	0.233	3,200,000
1.00	1.029	0.415	229,000	1.010	0.222	24,232,000
0.95	0.969	0.388	800,000	0.989	0.227	37,034,000
0.90	0.933	0.324	1,715,000	0.962	0.233	52,579,000
0.85	0.924	0.327	1,943,000	0.936	0.238	69,038,000
0.80	0.844	0.313	4,572,000	0.893	0.244	100,585,000
0.75	0.818	0.304	6,058,000	0.852	0.243	139,905,000
0.70	0.758	0.290	11,773,000	0.802	0.239	206,200,000
0.65	0.685	0.246	33,262,000	0.748	0.232	316,386,000
0.60	0.644	0.227	61,608,000	0.693	0.222	505,669,000
0.55	0.597	0.210	122,874,000	0.641	0.211	785,936,000
0.50	0.547	0.194	245,862,000	0.590	0.197	1,230,797,000
0.45	0.502	0.184	448,519,000	0.553	0.187	1,667,886,000
0.40	0.461	0.171	747,645,000	0.517	0.176	2,181,785,000
0.35	0.421	0.158	1,154,558,000	0.482	0.165	2,754,206,000
0.30	0.374	0.143	1,862,655,000	0.446	0.153	3,428,584,000
0.25	0.329	0.129	2,894,340,000	0.408	0.141	4,254,298,000
0.20	0.286	0.114	4,343,339,000	0.369	0.128	5,230,432,000
0.15	0.242	0.099	6,371,617,000	0.329	0.115	6,406,364,000
0.10	0.201	0.083	8,950,828,000	0.283	0.099	7,998,811,000
0.05	0.156	0.065	12,606,986,000	0.219	0.078	10,943,215,000
0.01	0.107	0.045	19,087,646,000	0.131	0.047	18,987,747,000

Note:

1) Cutoff grade intervals calculated from summation of modeled data (see Peterson, 2002d). For example, the 0.55 Cu cutoff includes all gridded data that falls between 0.575 and 0.525 wt. % Cu.

2) Cu%, Ni%, and tonnes represent cumulative addition of data from the Cu cutoff value and all data of higher grade.

3) Low Cu cutoff data dominantly represents barren rock within the mineralized zone of the Open style and barren rock above the mineralized zone within the Confined style.

4) Tonnes rounded to the nearest 1,000.

5) All intervals not assayed were assigned Cu and Ni values of 0.00 wt% and integrated into the model.

NICKEL LAKE MACRODIKE

Detailed geological mapping at a scale of 1:5,000 by the authors and Chris White, a Masters Candidate in the Department of Geological Sciences at the University of Minnesota Duluth, was completed in the late summer and fall of 2006, and published at a scale of 1:10,000 by the NRRI (Peterson et al., 2006). This map, available online at http://www.nrri.umn.edu/egg/REPORTS/MAP200604/MAP200604.html is the foundation upon which the field component of this trip will be based. During the course of this mapping, approximately 1,000 outcrops along nearly 100 kilometers of field traverses were examined to identify and confirm the internal lithologic variability, contact relationships, and structure of the western extent of the NLM, the adjacent SKI, and bounding rocks of the Anorthositic series. The authors wish to acknowledge Dr. Paul Weiblen (emeritus professor of geology at the University of Minnesota) for his keen insight on the geology of the area and Dr. George Hudak and undergraduate student Jeremiah

Gowey of the University of Wisconsin Oshkosh for assistance in mapping outcrops around and south of Omaday Lake. As well, a one day field excursion to Nickel Lake with Dave Peck (Anglo American), Harry Noyes (Encampment Resources), and Theodore DeMatties (consulting geologist) prior to the mapping campaign developed new insight on identifying dynamic magmatic systems in the field to the senior author (Peterson).

Additional reconnaissance mapping in early November by Dean Peterson was completed to field check compiled outcrop locations depicted on the 1957 INCO map of the Spruce Road Deposit and the 1968 Hanna Mining map of the South Filson Creek deposit (both of which are publicly available in the DNR archive at Hibbing, Minnesota). The reconnaissance mapping confirmed the location of gossanous Cu-Ni bearing INCO outcrops and reconfirmed the outstanding field mapping of all types of Duluth Complex rocks by Hanna Mining Company geologists of the late 1960s.

The NLM is a northwest to southwest-trending (Fig. 4.3), steeply dipping, asymmetric troctolitic and gabbroic intrusion interpreted to be a feeder dike for the northern portions of the SKI. The macrodike is interpreted to be located within a major rift-parallel normal fault (down to the southeast) now obscured by intrusion of NLM igneous rocks. Regional southward tilting (based on the deep level of erosion of the northern Bald Eagle Intrusion directly east of this area) leads to the interpretation that the southwest end of the NLM (near Omaday Lake) is structurally higher than the northeastern portion of the dike, and represents the location where magma flow changed from dike-like to sill-like, as it exited the dike – thus the magma velocity slowed – and entered the growing SKI magma chamber. Excellent potential exists for Ni-Cu rich massive sulfide at the basal contact where the dike enters the SKI (Section 31, T62N, R10W). The dike is composed of three main units: 1) inclusion-rich, locally sulfide-bearing, heterogeneous troctolite (unit N-Th); 2) layered troctolite, melatroctolite, and dunite (unit N-Tl); and 3) a late, cross-cutting, coarse-grained to pegmatitic oxide-rich, olivine-gabbro to melagabbro (unit N-xG).

Description of NLM Map Units

The basis for all of the field aspects of this field trip is the aforementioned recently published bedrock geologic map of the NLM (Peterson et al., 2006). As well, the description of “Field Trip Stops” to follow differ from most geology field trip guidebooks in that we are simply going to take some walks in the bush, mostly along logging roads and snowmobile trails, look at numerous outcrops of the NLM and adjacent rocks, and discuss the geology. We are NOT GOING TO SPECIFIC OUTCROPS to try to make a case for our interpretations; instead we urge you to use your imagination while we look at outcrops and add to the conversation. Instead of writing detailed descriptions of specific outcrops we’ll visit during the “stops” in the field trip, the authors have instead decided to simply copy verbatim the *Description of Map Units* from the map NRRI/MAP-2006-04 (Peterson et al., 2006) below, and use this as a reference during the field trip. The rocks of the NLM include, generally from youngest to oldest:

Oxide Gabbro (N-xG) - Dark-grey, coarse-grained to pegmatitic, recessive weathered, oxide-rich (magnetite and ilmenite), olivine-gabbro to melagabbro. Contains small inclusions of anorthosite (unit N-Ai), basalt (unit N-Bi), and troctolite (unit N-Th). Interpreted to be the youngest phase of the dike based on inclusion types and cross-cutting relationships.

Layered Troctolite to Dunite (N-Tl) - Grey to black, medium-grained, well-layered troctolite, melatroctolite, and dunite. Lamination of plagioclase and olivine parallel to modal layering is commonly observed as well as igneous scours and crossbedding. Small inclusions of anorthosite (unit N-Ai) and basalt (unit N-Bi) rare. Layering possibly developed as the up-welling magma streams through the dynamic (expanding) feeder dike. A constant temperature appropriate to plagioclase-olivine crystallization is maintained by a balance between the heat content of the incoming magma plus the heat of crystallization and the heat loss through the chamber walls.

Plagioclase and olivine are left behind and oriented/segregated on the walls of the expanding chamber (Weiblen, pers. comm.). Sulfide noted locally in outcrop in the SE corner of Section 31.

Heterogeneous Troctolite (N-Th) - Light to dark grey, medium- to coarse-grained, inclusion-rich, heterogeneous troctolitic rocks with local igneous scour structures. Unit composed of intermixed troctolite, anorthositic-troctolite, melatroctolite, and gabbroic phases surrounding numerous local country rock (unit N-Ai) and exotic (units N-IF and N-Bi) inclusions that are elongate parallel to the macrodike, as well as hosts the sulfide-bearing unit N-Ts. Interpreted to be the initial highly dynamic magmatic phase of the dike that carried exotic inclusions from deep in the crust to their present level.

Sulfide-Bearing Troctolite (N-Ts) - Rusty weathered, medium- to coarse-grained, sulfide-bearing, heterogeneous troctolitic and gabbroic rocks. Generally forms recessive weathering, Fe-stained, gossanous outcrops near, but not at, the northern margin of the macrodike. The current extent of this unit on the map is confined to those areas with outcrop, which in reality may be much more extensive as these outcrops generally end along linear swampy areas.

Anorthosite Inclusion (N-Ai) - Light-grey, medium- to coarse-grained troctolitic-anorthosite, commonly with 1-2 cm poikilitic olivine pits. The large anorthosite inclusions at the southwest end of the dike (around Omaday Lake) are interpreted to represent a "logjam" of blocks that quit moving due to the decreased speed of the macrodike magmas as they entered the South Kawishiwi Intrusion magma chamber. Includes blocks within the SKI adjacent to the Nickel Lake macrodike.

Basaltic Hornfels Inclusion (N-Bi) - Grey, fine-grained, steeply-dipping to vertical, granoblastic, locally magnetic, massive to amygdaloidal basaltic hornfels. Includes a highly magnetic block within the SKI adjacent to the Nickel Lake macrodike.

Biwabik Iron Formation Inclusion (N-IF) - Well-bedded, steeply-dipping, recrystallized (layered magnetite and pyroxenite) iron-formation commonly with disseminated Cu-Ni sulfides. Forms an intense localized positive magnetic anomaly.

- -

Anorthositic Series - Subsuite of the Duluth Complex composed predominantly of plagioclase cumulates displaying complex internal structure and lacking obvious signs of in situ differentiation. Occurs throughout the Duluth Complex as anorthosite, troctolitic-anorthosite, and gabbroic-anorthosite, commonly poikilitic.

Anorthositic Rocks Undivided (A-tA) - Mixed group of anorthositic cumulates occurring as large sill-like masses and as inclusions within troctolitic cumulates. Common rock types include troctolitic-anorthosite, leucotroctolite, anorthosite, and olivine-bearing gabbroic-anorthosite. Olivine ranges from 2 to 15 percent in mode and from granular to poikilitic in texture, with oikocrysts ranging from 1 to 3 centimeters in diameter. Plagioclase mode ranges from 75 to 95 percent and varies from being non-foliated to well-foliated. Inclusions range in size from a few centimeters to elongate bodies hundreds of meters long that are parallel to foliation in the enclosing troctolite.

DAY 1, FIELD TRIP STOPS

Traverse #1

The location of the first field trip traverse (#1) is given in Figure 4.7. This walk in the bush begins within numerous outcrops of the bounding Anorthositic series rocks (map unit A-tA) on the northern margin of the NLM. The trail will take us southwest into inclusion-rich heterogeneous troctolitic rocks (map unit N-Th) and into southwestern most zone of known Cu-Ni-(PGE) mineralization in the NLM (map unit N-Ts), which in this location is associated with a large, sub-vertical inclusion of Biwabik Iron Formation (map unit N-IF). One must try to imagine from where such an inclusion came from (see Figure 4.4), how it relates to the model that the NLM is a feeder dike to the SKI, why it and other large mapped inclusions in the NLM (Fig. 4.7) are concentrated at the southwestern end of the NLM (magma velocity). Think back to the previously described fundamental tenet of Ni-Cu-PGE magmatic sulfide deposits, "*… realization that decreases in the flow rate of magmas, principally due to the geometry of the conduit, is a major factor in settling entrained sulfide droplets and forming sulfide-rich ore bodies…*".

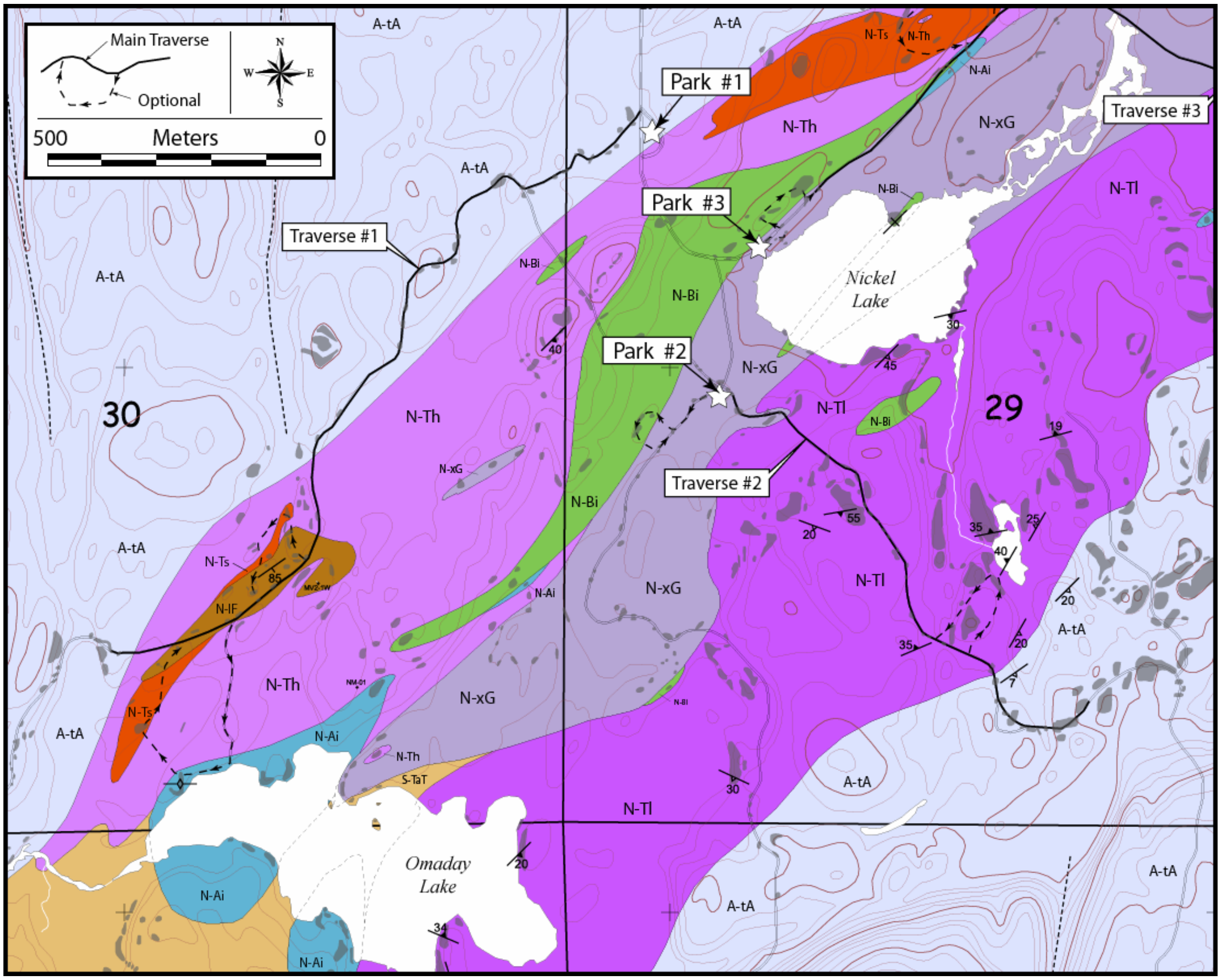

Figure 4.7. Bedrock geology map of portions of the southwestern end of the Nickel Lake Macrodike in Sections 29 and 30, T62N, R10W. Dark lines are superimposed locations of field trip traverse #1, and traverse #2 along logging roads and snowmobile trails. Dashed lines represent short traverses through the bush to additional known outcrops.

Traverse #2

The location of the second field trip traverse (#2) is presented in Figure 4.7. This walk to the southeast along a logging road/snowmobile trail begins in coarse-grained, oxide-rich olivine gabbro to melagabbro of map unit N-xG. Contact relationships between the N-xG and layered troctolitic to dunitic rocks (map unit N-Tl) can be complex, and we'll investigate these relationships early on the traverse. The bulk of this traverse will be through the widest section (>650 m) of unit N-Tl that has been mapped in the NLM. Careful attention should be directed towards igneous textures in the N-Tl, and what they imply to magmatic processes (expanding dike with time, modal layering, pasting plagioclase and olivine phenocrysts on dike walls, solidification fronts, etc…). Optional traverses shown include a walk to outcrops of the very large (~ 1.5 km long) basalt inclusion (map unit N-Bi), and to exceptional exposures of layered troctolite and dunite around a small beaver pond.

Traverse #3

The location of the third field trip traverse (#3) is presented in Figure 4.8. This walk to the north-northeast of Nickel Lake will traverse through most of the main units identified in the NLM, including map units N-Th, N-xG, N-Tl, N-Ts, N-Bi, and N-Ai. An important walk through the bush (optional traverse on Figure 4.8) will visit several Cu-Ni-(PGE) mineralized outcrops near the northwestern margin of the NLM, and allow us to view some spectacular exposures, around the margin of a drained beaver pond, of the Anorthositic series rocks immediately northwest of the NLM. The authors cannot speak to strongly on the importance of finding these types of exposures (totally free of lichen, moss, trees, etc…), early in a mapping program, as they provide proxies for subsequent mapping of outcrops deep in the bush, where trees, shrubs, shade, forest litter, dirt, and black flies partially obscure exposures and/or ones willingness to observe them.

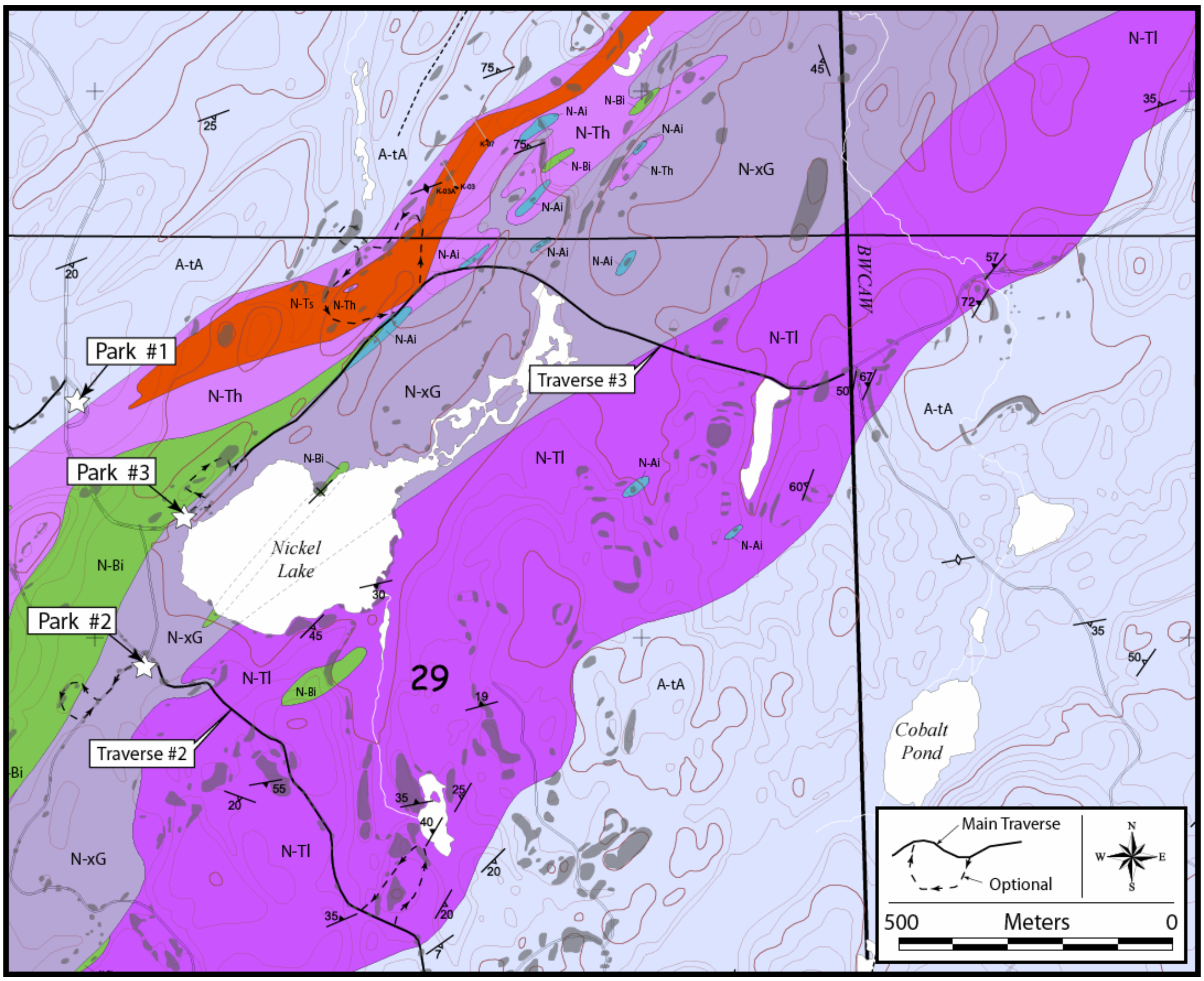

Figure 4.8. Bedrock geology map of portions of the Nickel Lake Macrodike in the vicinity of Nickel Lake, Section 29, T62N, R10W. Dark line in the center of the image is the superimposed location of field trip traverse #3 along a logging road. Dashed line in the northwest quadrant represents a short traverse through the bush into the Cu-Ni-PGE mineralized northern zone of the NLM. Note that beaver dams along the main traverse may cause very wet and/or impassable conditions.

Field relationships that offer evidence that a dike-like mafic to ultramafic intrusion is a conduit through which magma ascended upwards in the Earth's crust all lead back to the fundamental tenets of the Ni-Cu-PGE ore deposit model. Such relationships provide evidence that the rocks formed in a dynamic, sulfide-bearing magmatic system (once again, think like a person fly fishing a trout stream) that include: 1) early phases should be inclusion-rich (some of which should be from a deeper crustal level) and form as the igneous conduit breeches upwards into the Earth's crust; 2) imbrication and/or elongation of entrained country rock inclusions parallel to igneous foliation; 3) igneous scour structures; 4) prominent steeply-dipping igneous foliation and localized disruption due to magmatic injection; 5) cross-bedding of modal layering; 6) evidence of sulfide mineralization; and 7) evidence that that magma velocity varies. One of the authors' goals of the field trip is to expand this list based on conversations on the outcrop with the participants. Outcrop photographs given in Figure 4.9 show a few of these lines of evidence for the dynamic nature of the NLM.

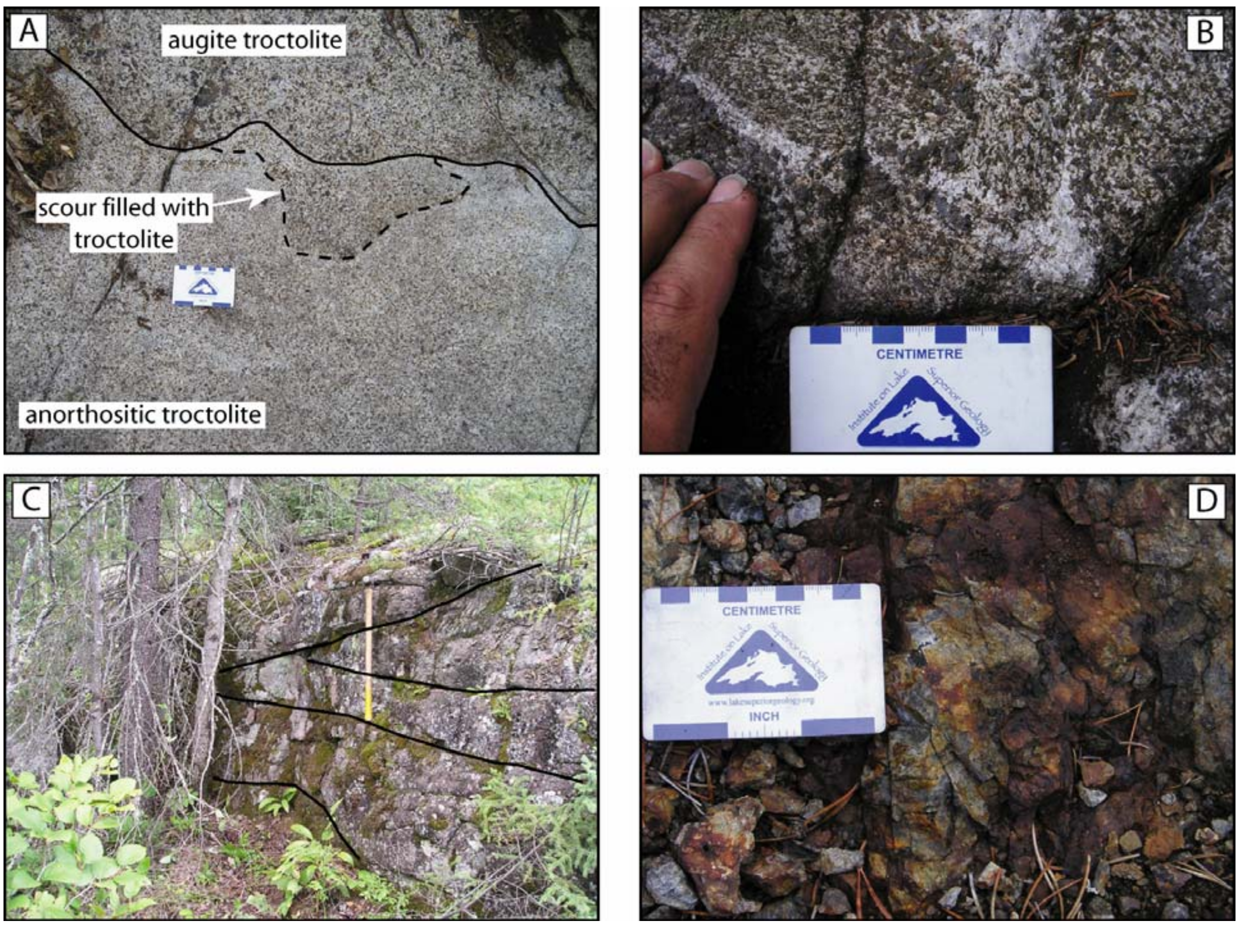

Figure 4.9. Photographs of selected outcrops that give us clues to the dynamic nature of the magmatic processes which ultimately led to the formation of the NLM, and by interpretation, the northern portion of the SKI and its associated Cu-Ni-PGE mineralization. A) Scour structure in map unit N-Th. B) Disrupted igneous foliation along the southern margin of map unit N-Tl. C) Cross-bedding of troctolitic rocks in map unit N-Tl. D) Cu-Ni sulfide mineralization in map unit N-Ts.

DAY 2, 3-D VISUALIZATION AND DRILL CORE DISPLAYS

Day two of this field trip will be spent at Duluth Metals Limited's field office and drill core logging facility in Ely, Minnesota. The day will be split up into two principal activities: 1) 3-D visualization of subsurface geological features of the Nickel Lake macrodike and South Kawishiwi intrusion utilizing the computer program gOcad (geologic object computer aided design) and a Geowall (bring your camera because we'll all be wearing those funny looking 3D glasses), and 2) examination of selected core intervals from a number of holes drilled by Duluth Metals Limited over the last year.

3-D GEOLOGICAL MODELING AND VISUALIZATION

The science of geology uses a variety of tools to study the earth. However, the basis for every type of geologic study is fundamentally rooted in observations made of rocks in their natural habitat – **"in the field"**. Geologists that do not have an intimate appreciation of the power and fundamental nature of field geology cannot, in turn, appreciate coherent and compelling field-based scientific arguments from which all other geologic interpretations grow. This basic tenet may never be truer than for geologists engaged in mineral exploration.

The advance in computer technology over the last twenty years has revolutionized all aspects of our lives. One such advance in geology has been the development of sophisticated 3-D geological software that, **if used correctly,** i.e., **created and maintained by geologists who understand the rocks**, can be an outstanding tool for letting geologists interpret data (field observations, drill hole data, etc...) into the subsurface where direct observation is impossible. The first author of this guidebook (Peterson) integrates many types of geological data into the computer program gOcad®, which is perhaps the most sophisticated 3-D geological modeling software available (see websites http://www.gocad.org/www/ and http://www.earthdecision.com/).

3-D models of active mines and/or advanced exploration projects benefit from continuous validation and upgrading of the underlying database, as well as the production of regional geological syntheses, integrating new geological, geophysical, geochemical, geotechnical, and geohydrological models into a single platform. The natural outgrowth of 3-D geological models is their extrapolation away from areas with large amounts of data to more remote areas with less and/or no data, and can assist in the definition of new exploration targets. For geologic teams working in a mineral exploration setting, the main advantages of using integrated 3-D geological models are to (from Fallara et al., 2006):

1) *Share the information*
    a. Conveys the data and their interpretation in an immersive format
    b. Avoids the loss of knowledge and interpretation which may be,
        i. Distributed within various locations within the company
        ii. Filed in disorganized ways
        iii. Never filed and existing only in a geologists memory
2) *Be a catalyst in the development of geologic knowledge*
    a. Easily integrates data in a common format
    b. Preserves data that is easily shared, seen, and analyzed
3) *Hastens problem solving throughout the company*
    a. Adaptable to team-driven resolution
    b. Easy access to geologists and management
    c. Allows for the shared comprehension of the data

4) *Accelerates the process of data integration and interpretation*
    a. Define potential exploration targets with reduced uncertainty
    b. Focuses work on interpretation
    c. Optimizes data subsets
5) *Direct access to data and manipulation within the gOcad® software*
    a. Integrated 3-D querying within the geological model
    b. Saves time and money, rapid validation of data, and uncertainty resolution

A 3-D display of the first author's gOcad modeling of geologic data from the Duluth Complex in general, and the SKI, NLM, and BEI in particular, will be presented in Duluth Metals Limited's drill core logging facility at the start of Day 2 of this field trip. A simple screen dump out of gOcad of some of this data is presented in Figure 4.10.

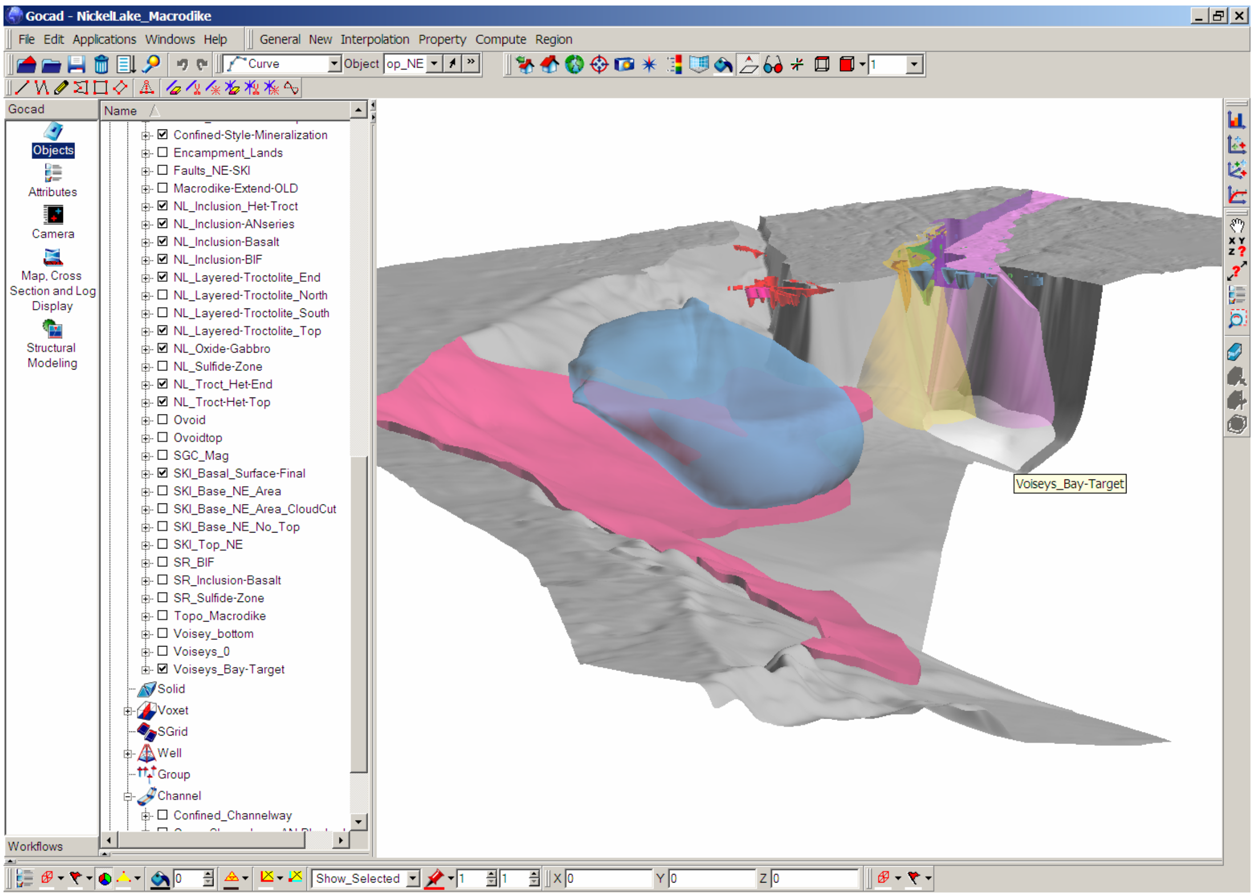

Figure 4.10. Print screen image of the SKI and NLM gOcad model (Peterson, unpublished data).

DULUTH METALS LIMITED DRILL CORE DISPLAYS

Recent drilling (Fig. 4.11) and core logging by Duluth Metals Limited east of the Maturi deposit in 2006 and 2007 has confirmed numerous stratigraphic units described by Severson (1994), especially the sulfide-bearing PEG, U3, BH, BAN, and upper GRB units.

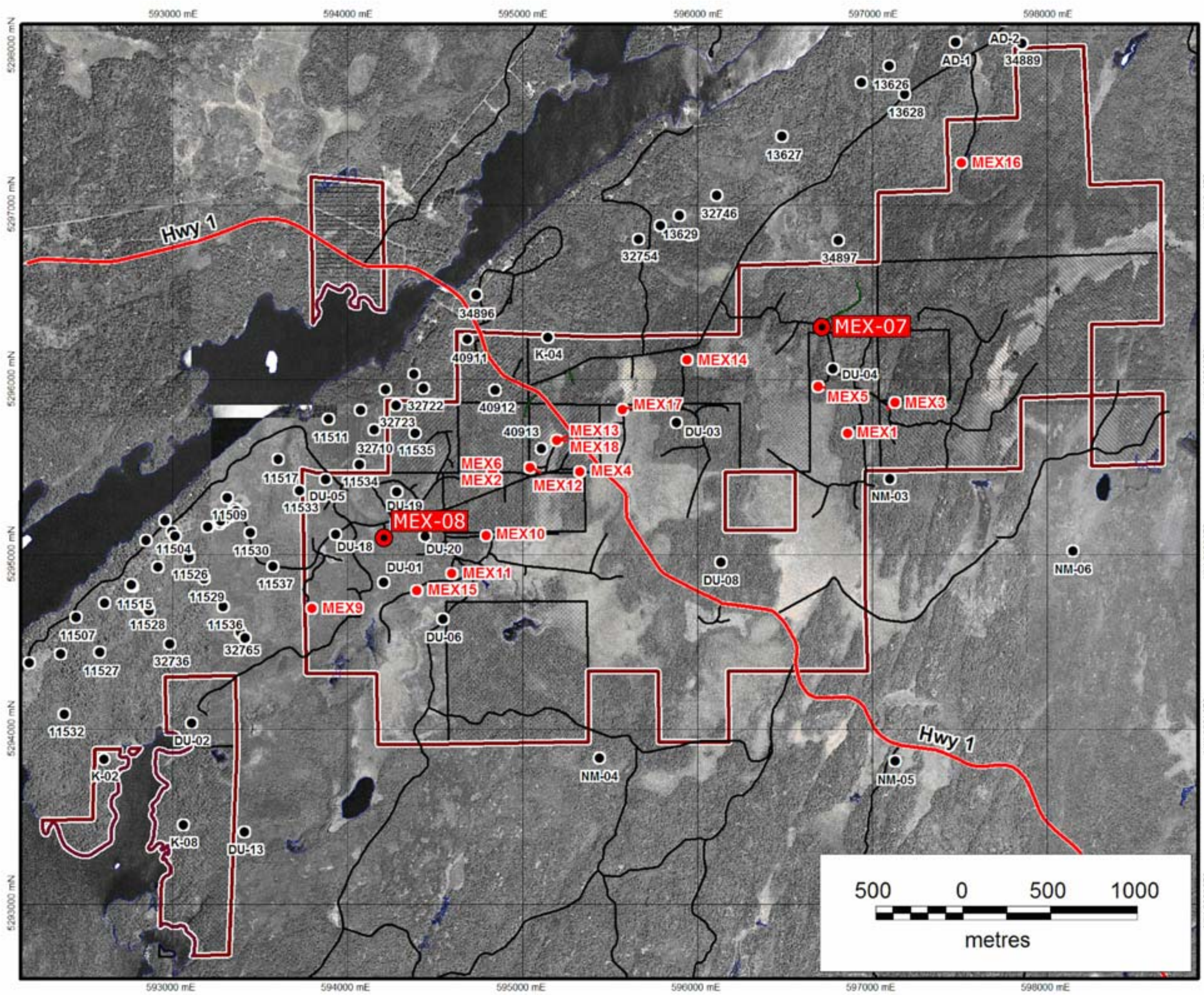

Figure 11. Property map of Duluth Metals Limited. Included are historic (black) and recent (red) drill holes.

The numerous correlative units of the SKI from historic and recent drill holes include the following:

Main AGT – Thick zone of homogenous augite troctolite to olivine gabbro.

AT&T – Thick zone of homogeneous medium-grained anorthositic troctolite with troctolites.

AT(T) – Homogeneous anorthositic troctolite grading to troctolite and lesser amounts augite troctolite.

T-AGT – Homogeneous medium-grained troctolite and augite troctolite.

Pic – Thin horizon of medium-grained picrite that is rarely developed, and thus usually uncorrelative.

Upper Gabbro – Heterogeneous, medium- to coarse-grained, oxide-rich gabbro and olivine gabbro.

AN Group – Combination of coarse-grained homogenous anorthosite, troctolitic anorthosite, anorthositic troctolite, and medium-grained homogeneous gabbro, and olivine gabbro of the Anorthositic series of the Duluth Complex.

Basalt Inclusion – Fine-grained, typically magnetic, basalt hornfels with sharp external contacts and locally preserved stretched amygdules.

U2 – Ultramafic horizon of locally serpentinized, medium-grained picrite and troctolite with sharp contacts.

PEG – Heterogeneous pegmatoidal and pegmatitic troctolite and anorthositic troctolite with minor amounts of augite troctolite, olivine gabbro, and troctolitic anorthosite. The PEG unit typically is weakly sulfide-bearing with sulfide-barren rocks above.

U3 – Ultramafic zone of locally serpentinized, sulfide-bearing, medium-grained dunite, picrite, and troctolite with sharp contacts. This unit is the PGE-dominate horizon at the Birch Lake deposit.

BH – Basal heterogeneous zone that is the main sulfide-bearing unit of the SKI. Consists of fine- to medium- to coarse-grained and pegmatitic troctolite and to a lesser extent anorthositic troctolite and augite troctolite.

BAN – Basal augite troctolite and norite which is the contaminated zone between the BH and underlying GRB. Consists of fine- to medium-grained, sulfide-bearing augite troctolite and norite.

GRB – A variety of rocks from the footwall Archean Giants Range Batholith. Rock types include medium- to coarse-grained hornblendite, diorite, and porphyritic or nonporphyritic monzonite to quartz monzodiorite. Sulfide mineralization is usually restricted to the upper 20 feet of the GRB, but can exist in small concentrations over a hundred feet into the granitic footwall.

Simplified drill hole logs portrayed as stratigraphic columns from two holes recently drilled in the eastern (MEX-07) and western (MEX-08) portions of the Maturi Extension deposit are presented in Figure 4.12. In addition, reported Cu-Ni-PGE grades from Duluth Metals Limited for these holes are given in Table 4.2. The stratigraphy observed in MEX-07 is typical of the eastern exploration area and the deep holes in this region (>3,000 feet) that are situated below a very large pillar/xenolith of Anorthosite series rocks (see Fig. 4.3). Channelized magma flow out of the NLM and under this Anorthosite block (think of eddies due to overlying friction as a fisherman would) has been interpreted by Peterson (2001b, c) as one of the driving mechanisms for enhanced turbulent flow of sulfide-bearing magmas, thus forming one of the elements of the Ni-Cu-PGE ore deposit model, *"an appropriate physical environment is required so that the sulfide liquid mixes with enough magma to become adequately enriched in chalcophile metals"*. The stratigraphy observed in MEX-08 correlates with many of the drill holes in the western exploration area (as well as Franconia Minerals', Maturi deposit) immediately to the west of the Anorthosite series pillar/xenolith. Mineralization in both of these holes consist of chalcopyrite-dominated disseminated sulfides (typically 2-5% total sulfide) restricted to a confined zone directly above the footwall and contain moderate to high Cu, Ni, and PGE concentrations.

If one would **very simply** (unlike the data depicted in Figure 4.6, which used the strict rules of Kerr, 2001) recalculate these reported grades (Table 4.2) to 100% sulfide, i.e. as a specific gravity concentrator would do as a first step at an active mine, then one would have to multiply the assay data by a factor between 20 to 50 (5% to 2% total sulfide minerals in the assayed drill hole intervals) to imagine the true reality that is the enrichment of Cu-Ni-PGE in the sulfide minerals of the Maturi Extension deposit. Such recalculations lead to grades (at 100% sulfide) of ~33% Cu, ~9% Ni, and ~11 – >82 g/t PGE+Au for the sulfide fraction of the Maturi Extension deposit, which point to these preliminary conclusions:

1) The extensive sulfide mineralization at the Maturi Extension deposit (as well as the Maturi, and Birch Lake deposits, i.e., the *Confined* mineralization of Peterson 2001, 2002a-d) is similar at a recalculated 100% sulfide grade to the metal budget of the fractionated residuum of a MSS;

2) One can imagine such mineralization (the *Confined*-style of Peterson 2002a) initially forming from incorporation of the Cu-PGE residuum of a fractionating Ni-rich MSS at the junction of the NLM and SKI into magmas streaming out of the NLM and into the SKI.

3) A seemingly robust geologic model of a dynamic magmatic system that incorporates the BEI, NLM, and the SKI exists herein that vector towards an exploration target for a Ni-rich massive sulfide body (the *"missing Ni-rich MSS")* at the junction of the NLM and the SKI.

Table 2. Reported mineralized intervals for holes MEX-07 and MEX-08 drilled by Duluth Metals Limited on the Maturi Extension property in 2006.

MEX-08	From (Ft)	To (Ft)	Total (Ft)	Cu %	Ni %	Pd (g/t)	Pt (g/t)	Au (g/t)
Overall	2032	2236.5	204.5	0.69	0.22	0.313	0.121	0.108
including	2052	2142	90	0.81	0.24	0.365	0.147	0.056
including	2202	2236.5	34.5	0.89	0.28	0.352	0.12	0.096

MEX-07	From (Ft)	To (Ft)	Total (Ft)	Cu %	Ni %	Pd (g/t)	Pt (g/t)	Au (g/t)
Overall	2543	2798	255	0.429	0.129	0.370	0.183	0.077
including	2608	2673	65	0.824	0.275	0.906	0.444	0.173
including	2628	2663	35	0.898	0.310	1.004	0.472	0.177

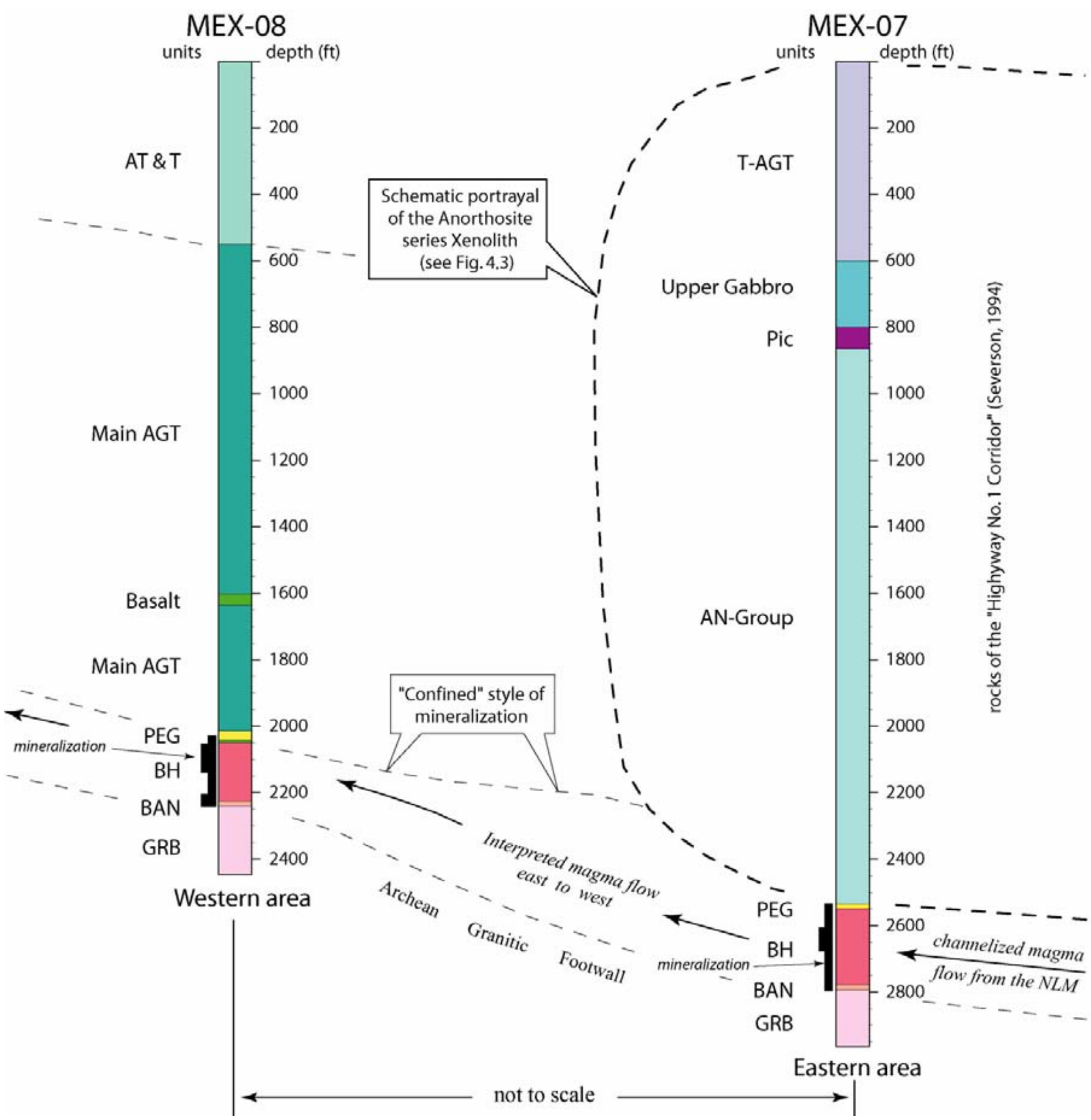

Figure 4.12. Stratigraphic sections of holes MEX-07 and MEX-08 drilled by Duluth Metals Limited on the Maturi Extension property in 2006.

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