IGNEOUS STRATIGRAPHY
OF THE
SOUTH KAWISHIWI INTRUSION,
DULUTH COMPLEX,
NORTHEASTERN MINNESOTA

By
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ABSTRACT

The Middle Proterozoic (1,099 Ma) intrusive Duluth Complex contains numerous smaller sub-intrusions that collectively comprise the Complex. Two of these sub-intrusions are informally known as the South Kawishiwi intrusion (SKI) and Partridge River intrusion (PRI). A correlative igneous stratigraphy has been documented in the PRI by Severson and Hauck (1991) and Severson (1991). In this investigation, detailed relogging of drill holes within the SKI (136 drill holes totalling 214,461 feet of core) also defines an intrusion-wide stratigraphic sequence along a 19-mile strike length that is referred to as the South Kawishiwi Troctolite Series (SKTS). The stratigraphic sequences of the SKI and the PRI are completely dissimilar. At least 17 correlative subhorizontal igneous units are defined within the SKTS; however, they are not equally present in all areas of the SKI. The SKTS units, from the bottom to the top (roughly), are referred to as: BAN = Bottom Augite troctolite and Norite; BH = Basal Heterogeneous troctolites (sulfide-bearing); U3 = Ultramafic Three (sulfide-bearing); PEG = Pegmatitic Unit of Foose (1984); U2 = Ultramafic Two (sulfide-bearing); U1 = Ultramafic One (sulfide-bearing); AT-T = homogeneous Anorthositic Troctolite to Troctolite; UW = Updip Wedge (sulfide-bearing); LOW AGT = homogeneous Lower Augite Troctolite zone; MAIN AGT = homogeneous Main Augite Troctolite zone; AT&T = homogeneous Anorthositic Troctolite and Troctolite; AT(T) = homogeneous Anorthositic Troctolite with lesser amounts of Troctolite; AN-G Group = intermixed Anorthositic and Gabbroic rocks; UPPER GABBRO = oxide-bearing gabbroic rocks; "INCL" = large shallow-dipping inclusion of magnetic basalt(?); UPPER PEG = Upper Pegmatitic zone; and T-AGT = Troctolite to Augite Troctolite (the latter five units are restricted to a small area referred to as the Highway 1 Corridor area).
The lowest units of the SKTS are the most varied with respect to textures, rock types, and sulfide content. They are very unevenly distributed along the strike length of the SKI in a ‘compartmentalized’ fashion suggesting a complicated intrusive history. The lowest units were emplaced early into several restricted magma chambers via repeated and close-spaced magmatic pulses. The effects of contamination from assimilated and devolatized country rocks were the most pronounced in these units. Three ultramafic-bearing packages (U1, U2, and U3 units) are also present within the lower portion of the SKTS. These units are characterized by alternating layers of troctolitic and ultramafic (olivine-rich) rock. The ultramafic-bearing units represent periods of rapid and continuous magma injection that crystallized more primitive ultramafic layers before mixing with the resident magma. The U3 Unit is the most unique in that it contains several massive oxide (magnetite-rich) pods along its strike length. An empirical relationship between the U3 Unit and the Biwabik Iron-formation (BIF) suggests that the massive oxides were derived from intruded and assimilated BIF. The U3 Unit also contains the majority of high Platinum Group Elements (PGE) values sampled to date in the SKI.

In contrast, the upper SKTS units reflect an entirely different intrusive history. Each unit is characterized by monotonous sequences of texturally homogeneous and sulfide-free rocks. Gradational contacts are present between each of the units. In contrast to the lower SKTS units, the upper SKTS units are generally distributed throughout the SKI. Ultramafic members are restricted to only two thin horizons referred to as High Picrite #1 and #2. All of these features are indicative of a quiescent and open magmatic system. Thus, the upper SKTS units appear to have been emplaced as widely-spaced pulses into a progressively developed, single magma chamber with little interaction with the country rocks.

An entirely different package of rocks is present in six extremely deep drill holes that were drilled within the Highway 1 Corridor (HIC). The HIC represents a large inclusion of older
Anorthositic Series rocks. It appears that the H1C rocks were underplated by the younger intruding SKI magmas.

Several drill holes within the PRI were also relogged to better understand the nature and location of the contact between the SKI and PRI. One important feature noted is that as the contact between the two intrusions is approached, the upper units of the PRI become heterogeneous and indistinguishable from each other. The same heterogeneity is not evident in the adjacent SKI. The presence of the 'heterogenous zone' within the PRI adjacent to the SKI suggests that the PRI was intruded before the SKI. Also present near the PRI/SKI contact zone is a major north-trending fault (down to the east). Associated with this fault are voluminous amounts of steeply-inclined lenses of late granitic/felsic material that cross-cut the PRI stratigraphic section. This fault is named the Grano Fault because the late lenses consist of varied granitic to pyroxenitic material. Though the Grano Fault trends through both the PRI and SKI, the late granitic lenses are not particularly common within the SKI. This fact also suggests that the PRI is older than the SKI. Offset units within the footwall rocks suggests that movement along the Grano Fault was initiated before emplacement of the PRI.

All geochemical data pertaining to previously sampled SKI drill core is compiled and correlated with the SKTS units. An additional 80 geochemical samples collected from SKTS units in this investigation are added to this database. The grouping of the SKTS units on the geochemical plots supports the geologic correlations of this investigation. Some of SKTS units also show geochemical overlap with footwall units and indicate the effects of contamination of the magma due to assimilation of the country rocks during intrusion.

PGE analyses conducted on a multitude of rock types and igneous units within the SKTS indicate that the U3 Unit, and to a lesser extent the PEG Unit, show the most promise of hosting a PGE deposit. The PGE origin model of Boudreau and McCallum (1992) is invoked to explain why
anomalous PGEs are common to the U3 Unit. The Boudreau and McCallum model envisions the upward migration of chlorine-rich, late, magmatic fluids that were capable of transporting PGEs and concentrating them at stratigraphic traps. However, a straightforward application of the model does not explain why significantly higher PGEs are restricted to certain areas, e.g., the Birch Lake deposit. A variation of the 'Boudreau and McCallum model' is proposed to explain this difference. This revised model is similar except that upward-moving, Cl-rich, PGE-pregnant hydrothermal solutions are envisioned to have been concentrated in fault zones. When fluids associated with fault zones encountered a proper stratigraphic trap (ultramafic horizon), more PGEs were deposited relative to areas outside of the fault zones. An intersection of the proper stratigraphic trap (U3 Unit with massive oxides, sulfides and high Cr contents) and the proper channelway to concentrate the PGE-pregnant Cl-rich solutions (Birch Lake Fault) reasonably explains the significant PGE values in the Birch Lake deposit. The Birch Lake Fault is defined by a zone wherein drill holes commonly encountered either: massive sulfide mineralization within the footwall granitic rocks; and/or 'voluminous' amounts of late granitic/felsic lenses that cut the troctolitic rocks of the SKI.
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INTRODUCTION

BACKGROUND

The Duluth Complex (Complex) is a large multiple intrusive body comprised of numerous smaller individual sub-intrusions. Recent studies have defined a previously unknown igneous stratigraphy within one of the sub-intrusions, informally known as the Partridge River intrusion (Fig. 1). The stratigraphy is defined in 144 drill holes within a 15-mile strike length (Severson and Hauck, 1990; Severson, 1991). These strata are exceptionally consistent and have since been extended to an additional 270 drill holes (Geerts et al., 1990; Geerts, 1991; Severson and Barnes, 1991; Hauck, 1993. Definition of the stratigraphy provides a framework by which mineralized zones (containing elevated values of Cu, Ni, Pd, Pt, Au, Ag) can be traced with more accuracy. However, similar large-scale stratigraphic studies are lacking within the South Kawishiwi intrusion, which is located to the immediate northeast of the Partridge River intrusion (Fig. 1).
The objectives of this investigation are to: 1) define the overall stratigraphy of mafic and ultramafic layered rocks within the South Kawishiwi intrusion through detailed relogging of existing drill core; 2) assign names to igneous units that are defined; 3) conduct a geochemical sampling campaign to characterize specific identified igneous units; 4) assemble all previously collected geochemical data, pertaining to drill core samples only, and assign to the data the appropriate igneous unit designators; 5) establish geochemical groups relative to the igneous stratigraphy; 6) compare the stratigraphy of the South Kawishiwi intrusion (SKI) to the stratigraphy of the Partridge River intrusion (PRI); and 7) provide additional data in the form of cross-sections and structural data to aid in understanding the origin of the Duluth Complex and its related Cu-Ni mineral deposits. This report is the culmination of a 1.7 year investigation involving relogging of almost all existing drill holes within the SKI and conducting geochemical sampling. Additional drill holes are also relogged in the extreme eastern portion of the PRI to better understand the nature of stratigraphic changes between the SKI and PRI.

GEOLOGIC SETTING

The Duluth Complex (Fig. 1) is a large, composite, tholeiitic mafic intrusion that was emplaced into comagmatic flood basalts along a portion of the Middle Proterozoic (1.1 Ga, Keweenawan) Midcontinent Rift System. The Complex is sporadically exposed in an arcuate belt extending a distance of about 150 miles northeastward from Duluth, Minnesota, toward the northeastern tip of Minnesota. Along the western edge, in the vicinity of Duluth, the base of the Complex is in sharp contact with volcanic rocks of the North Shore Volcanic Group (Middle Proterozoic-Keweenawan). Northward from Duluth, rocks that are footwall to the Complex include Lower Proterozoic metasediments of the Virginia/Thomson Formations and, in the vicinity of Babbitt, Minnesota, the underlying Biwabik Iron-formation. Northeast from Babbitt to the
Gunflint Trail, the footwall rocks of the Complex consist of Archean (2.7 Ga) granites and greenstones. East from the Gunflint Trail, at the basal contact are Lower Proterozoic Gunflint Iron-formation and metasedimentary rocks of the Rove Formation. At the upper contact (hanging wall) of the Duluth Complex are the comagmatic mafic volcanics of the North Shore Volcanic Group; however, because gradations between the two are commonly present, the ‘upper contact’ of the Complex is arbitrarily chosen in places (Weiblen and Morey, 1976).

Rocks of the Duluth Complex are varied and include a series of anorthositic, troctolitic, gabbroic, granodioritic, and granitic intrusive bodies. Generally, these have been divided into an Anorthositic Series and Troctolitic Series (Taylor, 1964) and a late differentiated Felsic series (Weiblen and Morey, 1980). Initially, rocks of the Anorthositic Series were inferred, on the basis of abundant field evidence, to have been emplaced early in the evolution of the Complex. However, recently acquired high-resolution U-Pb isotopic age dates indicate that Troctolitic and Anorthositic series rocks have indistinguishable crystallization ages of about 1,099 Ma (Miller, 1992; Paces and Miller, 1993). In view of these seemingly different observations, the Anorthositic Series is still considered to be older, but the two Series were emplaced in rapid succession (Miller et al., 1993). Age dates are also available on several of the smaller sub-intrusions that collectively comprise the Complex. These sub-intrusions, and their relative age (from Paces and Miller, 1993), are formally and informally referred to as: Logan Sills - 1,108 Ma (Davis and Sutcliffe, 1985); Nathan’s layered series - 1,107 Ma; Partridge River intrusion of Bonnichsen and Tyson (1975); South Kawishiwi intrusion of Green et al. (1966); Bald Eagle intrusion of Weiblen (1965); Powerline Gabbro of Bonnichsen (1972) - 1,099 Ma; and Lax Lake gabbro, Silver Bay gabbro (1,096 Ma), and Sonju Lake intrusion (1,096 Ma) of the Beaver Bay Complex (Miller, 1989). Many of these sub-intrusions, and additional unnamed sub-intrusions, of the Complex are delineated by Chandler (1990) on the basis
 regional stratigraphic setting of the South Kawishiwi and Partridge River intrusions relative to the country rocks they intrude. The range in age data suggest that the multiple intrusions of the Duluth Complex were emplaced within a 11-12 Ma range.

Two of the subintrusions of the Duluth Complex, the South Kawishiwi intrusion (SKI) and Partridge River intrusion (PRI), have been extensively drilled for Cu-Ni deposits. These intrusions and their potential Cu-Ni deposits are shown in Figure 1. The term ‘deposit’ is used loosely in this report to define areas where extensive exploratory drilling has intersected some Cu-Ni mineralization; to date, these deposits are subeconomic. The Cu-Ni mineralization is generally restricted to the basal 200-1,000 feet of both intrusions. Mineralized host rocks are augite troctolite and troctolite. Cu-Ni mineral phases consist predominantly of disseminated interstitial sulfides (1-5% volume in the intrusive rocks) of chalcopyrite, cubanite, pyrrhotite, and pentlandite. Also present in the Cu-Ni mineralization are minor amounts of sphalerite, galena, maucherite, millerite, mackinawite, valleriite, bornite, chalcocite, talnakhite, parkerite, native copper, native silver, native gold, platinum group minerals, and zincian hercynite. Massive sulfide is rare, but it is present within: 1) the Local Boy area of the Babbitt/Minnamax Cu-Ni deposit; 2) in the Serpentine Cu-Ni deposit; 3) in widely scattered pegmatitic zones in the troctolites; and 4) in widely scattered zones within the granitic footwall rocks. Massive sulfide minerals are essentially the same as those in the disseminated ore.

The regional stratigraphic setting of the PRI and SKI relative to the country rocks they intrude is depicted in the schematic section of Figure 2. Generally, metasedimentary rocks of the Virginia Formation are the dominant footwall rock
of the PRI, and granitic rocks of the Giants Range Batholith are the dominant footwall rocks of the SKI. The Biwabik Iron-formation is present at the basal contact in portions of the PRI (in the extreme northeastern end) and portions of the adjacent SKI (in the southwestern end). Inclusions of hanging wall rocks are present within both intrusions and include: basalts of the North Shore Volcanic Group; magnetite-rich basalts ('Colvin Creek Hornfels'); and locally, quartzite inclusions found near the base of some basalt inclusions (Nopeming Formation - early Keweenawan?).

Emplacement of the Complex occurred during an episode of extensional tectonism that produced the Midcontinent Rift System. Weiblen and Morey (1980) presented a half-graben model for the overall emplacement style. They envisioned a step-and-riser configuration of the basal contact, due to steep, southeast-dipping, northeast-trending normal faults. According to the model, magma was injected into fault-bounded voids formed during rifting to produce multiple smaller intrusions that collectively comprise the Complex. Weiblen and Morey (1980) also suggest that these northeast-trending faults may be offset by a series of northwest-trending strike-slip (transform) faults. This model is consistent with the two fault directions recognized in the SKI (Foose and Cooper, 1981) and in a lineament study conducted by Cooper (1978). Several north-south and northwest-trending faults are located to the immediate north of the Complex in exposures of open pit iron mines (Holst et al., 1986). However, because the faults cannot be traced with certainty southward into the Complex, the authors feel that the half-graben model is not fully substantiated.

A recent study of faults within the Peter Mitchell Mine (Fig. 1) suggests that several north and northeast-trending faults are present (Severson, in prep.). The majority of these faults exhibit increased amounts of relative motion toward the Complex ('scissors-type' faults) which suggest they formed during emplacement of the Complex (Severson, in prep.). Additional studies also document the existence of northeast-trending faults within the Complex, in accord with the half-
graben model, and these include: Geerts et al., 1990; Severson and Hauck, 1990; Geerts, 1991; Hauck, in prep; and Zanko et al., 1994. Almost all the northeast-trending faults offset both the footwall rocks and the troctolitic rocks.

PREVIOUS INVESTIGATIONS

Within the South Kawishiwi intrusion over 640 drill holes were put down in search of Cu-Ni mineralization. Out of this set, 226 drill holes are still intact and can be utilized to define the stratigraphy present within the SKI. Unfortunately, very little detailed work, in the form of relogging and correlating units in drill core, was conducted prior to this investigation. Bonnichsen (1972) logged and correlated three igneous units within four drill holes (NM-5, NM-7, NM-9, NM-11) in the Dunka Pit area (section 2, T.60N., R.12W.). To the northeast of this area, Foose (1984) logged and correlated nine drill holes (Du-6, Du-8, Du-10 through Du-17) over a 6 mile strike length that defined six igneous units. Individually, these two studies establish that correlative igneous units can be defined within the SKI. Unfortunately, the two researchers used different logging criteria, and their stratigraphic packages cannot be easily compared to each other. Furthermore, attempts to compare these two stratigraphic packages are hampered by the fact that the strata present in each area are not identical! Results of this investigation indicate that not all the specific units of one area are present throughout the SKI because some units exhibit interfingering and/or pinch-out relationships. Most recently, Kuhns et al. (1990) logged and correlated 24 shallow drill holes (generally <300 feet deep) in the South Filson Creek Cu-Ni deposit area.

Single drill hole studies are also extremely limited within the SKI. Fukui (1976) conducted petrographic and mineral chemistry studies on drill hole NM-5 (and to a lesser extent NM-7, NM-9, NM-11) in the Dunka Pit area. There are several investigations concerning Platinum Group Element (PGE) mineralization in drill holes Du-15 and Du-9 of the Birch Lake deposit. These include:
Sabelin and Iwasaki (1985, 1986), Dahlberg (1987), and Alapieti (1991). Much of this research was sparked by the discovery of up to 9.1 ppm Pd + Pt associated with a massive oxide zone in Du-15.

Detailed geologic mapping was undertaken within portions of the SKI (Green et al., 1966; Bonnichsen, 1968; Morey and Cooper, 1977; Foose and Cooper, 1978). While these mapping endeavors portrayed the spatial geologic and structural relations, they were inadequate in terms of defining a detailed igneous stratigraphy within the SKI.

PRESENT INVESTIGATION

This report is a summary of activities conducted from October 1991 to June 1993. To date, 136 drill holes (214,461 feet of core) were relogged in detail from the SKI and portions of the PRI (northeastern end). An additional 54 holes were also scanned for major lithologic breaks. Zanko et al. (in prep.) logged an additional 31 drill holes in the Serpentine Cu-Ni deposit area (Fig. 1). In essence, almost all drill holes that were put down into the SKI, and are still preserved intact, were examined during the report period. A total of 193 holes were looked at in some form. A listing of all known holes drilled within the SKI are included in the SOKALITH.WK1 data file (back pocket). Major lithologic breaks within each of the drill holes are also listed in the data file.

Almost all of the drill core is stored at the Minnesota Department of Natural Resources (MDNR) core storage facilities in Hibbing, Minnesota. Additional holes (K- prefix) are stored at the Midland Research Center in Nashwauk, Minnesota. In most cases, the entire drill core has been preserved, with two exceptions. The NM drill holes often have large internal gaps where up to 270 feet of core is missing. The missing zones usually contain sequences of the Biwabik Iron-formation that were probably removed for metallurgical testing. Near the bottom of several Du holes, quartered core (split) from two core boxes has been commonly transferred to one box. This disastrous situation usually occurs at and above the basal contact for several hundred feet. In some
cases the boxes have been tilted and the quartered core is jumbled and mixed. Sometimes the jumbled core box contains rocks of both the Complex and the Giants Range Batholith, and the exact footage of the basal contact is arbitrarily chosen. These unfortunate circumstances occurred before the MDNR acquired the drill core.

After the majority of the drill holes in a specific area were logged, cross-sections were constructed and individual rock units were correlated. In this manner, a particular bias of ‘looking for’ a specific horizon was minimized. Several cross-sections and hung-stratigraphic sections were prepared (Plates III through XV). The locations of the cross-sections are shown on Plates I (A & B), and XV-A. All drill hole locations, shown on Plates I, II, and XV, have been thoroughly researched and corrected within the limits of the existing database at the MDNR or from data acquired from private company files. Structure contours of the basal contact are included in Plates II (A & B) and XV-B.

Most of the major igneous units defined within the SKI are sampled for geochemical analyses. Eighty samples were collected for whole rock, base metal, trace element, precious metal, and REE analyses. The samples were analyzed by X-ray Assay Laboratories in Don Mills, Ontario, Canada. Platinum Group Element (PGE) scans were conducted by Dr. Sarah-Jane Barnes of the University of Quebec at Chicoutimi (data are included in the computer disk in the back pocket of this report). Also, all previously collected geochemical data, sampled from drill core, are assembled and correlated with specific stratigraphic igneous units that are defined in this study. These data are from: Dahlberg, 1987; Dahlberg et al., 1989; Sabelin and Iwasaki, 1985; Sabelin and Iwasaki, 1986; and private company records located in the exploration files at the MDNR (data also on computer disk in the back pocket of this report). Base metal analyses (Cu, Ni, Fe, S) that were originally conducted for the exploration companies that drilled the hole are not included in this report. These
data are listed and can be found on copies of the exploration company’s drill log on file at the MDNR.

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DRILL CORE LOGGING

Detailed relogging of hundreds-of-thousands of feet of drill core was necessary in order to define correlative intrusion-wide stratigraphic sequences within both the PRI and SKI. During the last six years, 550 drill holes (634,000 feet of drill core) from within the PRI and SKI were relogged by Natural Resources Research Institute (NRRI) personnel and are reported in: Severson and Hauck (1990); Geerts et. al. (1990); Severson (1991); Geerts (1991); Severson (this investigation); Hauck (1993); Hauck (in prep.); and Zanko et al. (in prep.). The original exploratory drill logs are available for each of the drill holes, but they are utilized to a very small degree. This is because the hundreds of holes within the Complex were originally logged by many different geologists, each using a different classification system, or each emphasizing different aspects or rock types of the Complex. Obviously, most of the original logs cannot be used to define intrusion-wide correlative units. In order to avoid this type of confusion, the geologists at the NRRI used the same classification system for rock names. They also attempted to correlate the igneous units with the units originally defined by Severson and Hauck (1990). However, because internal stratigraphic changes are present within both intrusions, correlation with the original igneous units was not always possible and additional units were progressively added as more areas were investigated, e.g., Severson, 1991; Hauck, 1993.

In this investigation, rock types of the Duluth Complex are classified according to the scheme depicted in Figure 3. The igneous rock names are based on visually estimated modal percentages of plagioclase, olivine, and pyroxene. When there is a dramatic fluctuation in the modal
percentages of minerals, either an average rock name is assigned, or a range of two rock type names is assigned to the particular interval, e.g., troctolite-anorthositic troctolite. In some cases, there is such extreme variations in modal percentages that a particular interval is simply designated as 'het' for heterogeneous. Picrite (melatroctolite) and peridotite are collectively referred to as ultramafic rocks/layers in this report. Some highly heterogeneous zones consist of alternating fine-grained and coarse-grained troctolites - these are referred to as '2T,' which denoted 'two troctolite varieties.' INCO geologists referred to these types of highly heterogeneous zones as 'Spruce Breccia' because they felt that the fine-grained troctolitic material represented inclusions of earlier chilled material within a later coarser-grained troctolite. The modifier 'oxide-bearing' and 'sulfide-bearing' refers to zones with >10% oxides and >0.5% sulfides, respectively. Grain size modifiers are used as follows: fine-grained = 1-2 mm; medium-grained = 2-5 mm; coarse-grained = 5-10 mm; pegmatoidal = 10-20 mm; and pegmatitic = >2 cm (up to 5-8 cm).

Field terms are assigned to the granitic rocks of the Giants Range Batholith (GRAN) and to late granitic/felsic rocks (gr) that intrude the troctolitic rocks of the Complex. Because both these two rock groups consist of numerous rock types, only the terms 'GRAN' and 'gr' are listed on the cross-sections of this report. Some of the granitic rocks were sampled for thin section inspection and potassium feldspar staining. These rocks were then classed according to the classification scheme of Streckeisen (1976).

Figure 3. Rock classification (after Phinney, 1972).
During relogging of the drill core an attempt was made to relog all drill holes within one deposit area before progressing to another deposit area. After all the holes were relogged in a particular area, the data were plotted on ‘hung’ stratigraphic sections (Plates III, IV, and V), and specific rock units and/or rock packages were correlated between drill holes. A ‘hung’ section is a pseudo cross-section where the drill holes were ‘hung’ according to a specific datum, e.g., the top or bottom of a clearly recognizable and laterally persistent ‘marker bed.’ When the drill holes were portrayed in this manner, other significant marker horizons were then correlated between drill holes. Within the PRI the rock units were designated as Units I through VII (Severson and Hauck, 1990; Severson, 1991). In order to avoid confusion, units within the SKI were assigned abbreviated names, e.g., MAIN AGT for Main Augite Troctolite or U3 for Ultramafic 3. Because very little core remains for the holes put down within the Spruce Road Cu-Ni deposit, this approach was not possible. In this instance, the few remaining intact drill holes were relogged and rock units were correlated with outlying areas. The relogged holes were then compared to the original INCO exploratory drill logs and corresponding units were found according to the INCO terminology. Plate XV-D was an attempt to expand the units of this investigation to a longitudinal section through the Spruce Road Cu-Ni deposit using the INCO exploratory drill logs.

It is important to remember that the intrusion-wide strata depicted in this and previous NRRI reports are still somewhat generalized. Even though the PRI and SKI strata are defined by hundreds of drill holes, it is not uncommon to find a particular drill hole that partially or totally deviates from the ‘norm.’ Therefore, the PRI and SKI stratigraphies shown in Figures 8 and 10 are only general stratigraphic sections that represent the majority of drill holes logged to date - some variations can be expected to be locally present. Many of these local variations are shown on all the cross-sections (Plates III through XV) and are readily observed only when the cross-sections are closely scrutinized. Broad variations, similar to facies changes, are also present from deposit area
to deposit area. These are especially evident within the SKI, but can occur in the PRI as well. For example, Unit II of the PRI exhibits at least three ‘facies changes’ along strike from the Wyman Creek Cu-Ni deposit to the Wetlegs Cu-Ni deposit to the Dunka Road Cu-Ni deposit. Also, in the Bathtub area of the Babbitt Cu-Ni deposit, numerous ultramafic horizons are present within Units IV, V, and VI suggesting another ‘facies change’ (Severson, 1991). This package of alternating troctolites and ultramafics has been informally named the 'Bathtub Layered Series' (Hauck, 1993).

In viewing the cross-sections of this report, it is important to keep in mind that lateral changes can occur in a particular igneous unit. Even though an intrusion-wide stratigraphic package has been defined, there are also numerous pinch-outs, variable unit thickness changes, and lateral lithologic changes. Not all of these variations are described in detail, but they can be recognized on the accompanying cross-sections.

DEFINITION OF PETROGRAPHIC FEATURES

During the study period, 911 samples were collected from various troctolitic rocks, inclusions, late intrusive rocks, and the various footwall rocks for petrographic examination. Modal percentage estimates were conducted on all the troctolitic rock samples. An additional 223 thin sections stored at the MDNR were reviewed for distinguishing petrographic features. A detailed description of types of cumulus and intercumulus minerals present within the troctolitic rocks of the PRI was previously presented by Severson and Hauck (1990), and Severson (1991). These same descriptions apply to the troctolitic rocks of the SKI and will not be reiterated here. However, unique petrographic features are briefly described below.

Symplectite
**Plagioclase Symplectite** - wormy intergrowths of hypersthene and plagioclase at the edges of plagioclase laths in contact with olivine. This reaction product replaces plagioclase laths from the edges inward and resembles a ‘front’ in that its innermost boundaries are sharp and lobate.

**Olivine Symplectite** - wormy iron oxide and hypersthene replace the outermost portions of olivine. The wormy iron oxide consists of composite magnetite and ilmenite; magnetite is the dominant phase.

**Oxides** - occur as either interstitial composite ilmenite-magnetite grains or round adcumulus grains. Throughout this report the following terminology is used for the interstitial composite oxide grains: ilmenite>magnetite defines ilmenite grains with lesser amounts of composite magnetite; magnetite>ilmenite defines magnetite grains with lesser amounts of composite ilmenite. Adcumulus magnetite grains are found exclusively within massive oxide horizons, oxide-rich ultramafic layers and inclusions of Biwabik Iron-formation (round magnetite).
REGIONAL GEOLOGY - DESCRIPTION OF MAJOR ROCK UNITS

INTRODUCTION

Before the igneous stratigraphy of the SKI and PRI can be discussed, it is necessary to describe the older rocks into which both intrusions were emplaced. The older rocks are present in the footwall of the Complex and as inclusions located near the basal contact of the Complex. Hanging wall rocks are also present as inclusions within both the PRI and SKI. Late intrusive rocks that cross-cut the troctolitic rocks of both the PRI and SKI are discussed. A brief description of fault zones within the PRI and SKI are also presented in this section.

ARCHEAN ROCKS

Giants Range Batholith (GRAN)

Rocks that are footwall to the SKI are dominantly granitic rocks of the Giants Range Batholith (GRAN) that crop out to the northwest of the SKI (Plate I). The Giants Range is composed of many separate plutons that were intruded into a metavolcanic/metasedimentary 'greenstone' terrain during the Algoman orogeny (approx. 2.7 Ga). Rocks of the batholith (in drill holes relogged in this investigation) are varied and include granite, monzonite, quartz monzonite, monzodiorite, quartz monzodiorite, granodiorite, and diorite. Locally present are syenite, quartz syenite, tonalite, hybrid rocks, and scattered hornfelsed inclusions. All rock types are commonly intruded by near vertical veins and dikes of pink aplite and minor vein quartz. This assortment of granitic rocks is referred to as GRAN on the cross-sections of this report.

In numerous drill holes, the GRAN rocks immediately below the basal contact of the Complex exhibit the effects of contact metamorphism, i.e., partial melting and recrystallization. This is expressed by a gradational increase in quartz content and potassium feldspar (K-spar)
content, or pink color in drill core, with depth (up to 210 feet) below the basal contact. K-spar depleted zones are indicated on the plates of this report by the symbol "cn," which is a logging term used to denote 'contaminated zones.' Bonnichsen (1972) also recognized this color/compositional change with depth within the Dunka Pit area. He stated (p. 367) that "... the uppermost 50 to 100 feet of granite in the footwall has less K-feldspar than the deeper parts. Adjacent to the contact, the rocks are thoroughly recrystallized and most contain hypersthene. Many are dioritic in composition, but [are] similar in appearance to ... rocks that characterize the Giants Range Granite ... at greater depth in the drill holes. The apparent loss of K-feldspar suggests that the rocks immediately below the contact were partially melted, and that a 'granitic' fraction was lost. Probably, the noritic part of the overlying basal intrusive unit in large part owes its chemical nature to assimilation of the materials that were distilled out of the underlying Giants Range Granite."

Disseminated sulfides may be present sporadically in the uppermost 330 feet of the GRAN below the basal contact of the Complex. In some of these cases, sulfide mineralization begins immediately below the basal contact within the first 100 feet of the GRAN. However, in some drill holes the first 100 feet is sulfide-barren, but sulfide mineralization is present at depths of 200-300 feet below the basal contact. Sulfide mineralization is associated with both 'contaminated' and 'fresh' GRAN. Within these zones chalcopyrite is the most dominant sulfide; whereas, pyrrhotite is the dominant sulfide in the overlying igneous rocks of the Complex. Good disseminated mineralization (>1% over 40 feet) occurs in drill holes D-2, D-3, D-4, D-5, E-5, C-88-1, BL-90-2, Du-5, K-1, and NM-4 (Plate I). Massive sulfide veins and irregular pods are also found within the uppermost 100 feet of the GRAN. These massive sulfide occurrences are generally pyrrhotite-rich, but they have much higher Cu and Ni values than the massive sulfides located in Complex rocks. Cu and Ni values for the massive sulfides in the GRAN are listed in the SOKAWR.WKI file (computer disk in back pocket). GRAN-hosted massive sulfides occur in the following drill holes:
NM-28, D-2, D-5, D-12, Du-1, Du-12, Du-13, BL-90-2, K-8, and 32781 (Plate I). Small irregular massive sulfide blebs are also found in drill holes: Du-7, Du-14, BL-89-1, and BL-90-1 (Plate I). Collectively, the GRAN massive sulfide occurrences and the GRAN disseminated mineralization outline two northeast trending belts (Fig. 4). The linearity expressed by the belts suggests that they are fault controlled. Interestingly, one of these linear belts, named the Birch Lake Fault, trends through an area where high Pt and Pd values have been found in the overlying Complex rocks (Sabelin and Iwasaki, 1985, 1986). This association is more fully addressed later in this report.

Bonnichsen et al. (1980, p. 562) states that sulfide-bearing zones in the GRAN are '...related to the availability of channelways for the sulfides to travel through, and be deposited in, while the [basal units of the SKI] were forming. The restriction of the epigenetic sulfides [to zones separated by barren rock] suggest [that] these zones were initial permeable features in the Giants Range batholith or were produced while the rocks were hot. The lack of any obvious indication of faulting in association with these zones suggests their formation did not involve much fault motion or that subsequent complete healing during high-temperature recrystallization eliminated the evidence....The existence of these epigenetic sulfide zones, to nearly 100 meters vertically beneath their probable source at the base of the complex, is in itself very instructive, as it shows the great mobility of sulfide melts through essentially solid rock at high temperatures.' They also note that the sulfide-bearing zones are copper-enriched relative to the overlying Complex rocks and state that it '... probably resulted because fractional crystallization caused Cu enrichment in the melts as they trickled downward through a decreasing thermal gradient beneath the complex.' (Bonnichsen et al., 1980, p. 563)
Figure 4. Distribution of sulfide mineralization within the Giants Range Batholith (beneath the Duluth Complex).
LOWER PROTEROZOIC ROCKS (ANIMIKIE GROUP)

Lower Proterozoic rocks (1.8 Ga) in northeastern Minnesota are collectively referred to as the Animikie Group (Sims and Morey, 1972). These rocks are represented by three formations that are, from oldest to youngest: the Pokegama Quartzite; the Biwabik Iron-formation; and the Virginia Formation. These units represent a single depositional event characteristic of a transgressing sea, beginning with clastic materials of a stable shelf and ending with muddy and turbidite material of a deep basin (Morey and Ojakangas, 1970). Dips of $3^\circ$-$20^\circ$ are characteristic of these formations when they are present beneath the Duluth Complex.

Pokegama Quartzite

At the base of the Lower Proterozoic section is a sequence of interbedded quartzite, metasiltstone, argillite, and localized quartz-pebble conglomerate that is collectively referred to as the Pokegama Quartzite. The Pokegama is only locally present beneath the Biwabik Iron-formation and both formations unconformably overlie Archean rocks. The Pokegama was intersected in only 15 drill holes (SOKALITH.WK1); a maximum thickness of 25 feet was intersected.

Biwabik Iron-formation (BIF)

The Biwabik Iron-formation is an alternating sequence of ferruginous chert and slate that is selectively mined for its iron content. Taconite is an economic term that refers to those portions of the iron-formation that can be profitably mined (Morey, 1993). The Biwabik Iron-formation is exposed in an east-west trending belt that is referred to as the Mesabi Range. Within the vicinity of the SKI the Biwabik Iron-formation is approximately 400 feet thick. It generally dips about $3^\circ$-$10^\circ$ to the southeast but exhibits steeper dips of up to $20^\circ$-$40^\circ$ in the extreme eastern portion of the Mesabi Range where the BIF is in close proximity to the Duluth Complex. Locally the BIF is
footwall to the SKI and PRI (see Plates II-A and II-B). Adjacent to and beneath the Complex, the intensity of metamorphism within the BIF increases to pyroxene hornfels facies in the Dunka Pit and Peter Mitchell Mine (Bonnichsen, 1968; French, 1968). Also in Dunka Pit, where the BIF is in direct contact with the Complex it exhibits elevated Ti contents. This suggests that movement of titanium occurred across the contact into the BIF during metamorphism of the BIF (Muhich, 1993a; 1993b).

The BIF is divided into four main members that have been further divided into several submembers. A brief description of the BIF submembers, and thickness ranges, are presented in Figure 5. This figure is based on the extensive investigations of Gundersen and Schwartz (1962) who originally devised the BIF submember classification scheme. Thickness ranges for the uppermost 15 submembers (A through O) have been revised in this study. The thickness range of submembers A through D is based on thicknesses reported in over 100 drill hole logs along the southern edge of the Peter Mitchell Mine (Fig. 1). Specific submembers of the BIF that were recognized during relogging of drill core are described in more detail below.

Submember A - This unit consists of interbedded white chert and medium-grained white marble. Both chert and marble are generally present within A, but locally only one of the two may be present. Near the base of submember A, the marble contains diopside-rich beds that are characteristic of submember B. In general, these
Figure 5. Stratigraphy of the Biwabik Iron-formation in the eastern Mesabi Range (modified from Gundersen and Schwartz, 1962). Basal portion of Virginia Formation is shown.
diopside-rich beds increase in number with depth within submember A, whereas the marble beds exhibit a concomitant decrease with depth. This relationship indicates that the contact between submembers A and B is transitional. In the Dunka Pit mine, large ovoid diopside-rich 'clasts', up to 1-2 feet long, are locally present within the marble of submember A.

Submember B - This submember consists of irregularly-interbedded white chert beds and moderate-green diopside-rich beds. Bedding planes between the two varieties are extremely irregular, forming lenses that vary from 1 inch to over 1 foot thick. White marble beds may be present within the top few feet of submember B.

Submember C - This unit is the uppermost submember of the BIF that contains appreciable amounts of magnetite. It consists of very well-laminated gray, black, and green beds of chert, magnetite, and silicates, respectively. Gundersen and Schwartz (1962) report that the silicate beds consist of ferrohypersthene with lesser amounts of hedenbergite, fayalite, and cummingtonite.

BIF Sill - Within the center of submember C is a 2-18 foot thick, fine- to medium-grained diabasic to granoblastic sill. Major constituents of the sill, in decreasing order, are: plagioclase (45-65%), orthopyroxene (8-45%), and amphibole (1-18%) with minor amounts of olivine, clinopyroxene (Cpx), inverted pigeonite, and biotite. Trace amounts of ilmenite (minute round 'drops'), sulfides (dominantly pyrrhotite), and apatite are also found within the BIF Sill. Commonly, the top and bottom few inches of the sill are chilled against submember C. Within the Peter Mitchell Mine, the top of the BIF Sill exhibits polygonal cracks within the
chilled zone. Also in a localized area of the mine, the BIF Sill contains plagioclase phenocrysts up to 4 inches across.

Although the BIF Sill does not appear to be metamorphosed in hand sample, the effects of metamorphism are more obvious in thin section as shown by a granoblastic texture that is developed to varying degrees. This variability in texture suggests the BIF Sill may be an early Duluth Complex intrusive event (Logan Sill age?) that was subsequently metamorphosed by later intrusions of the Complex, e.g., SKI and PRI. At least two sills are present above the BIF within the Virginia Formation (see Fig. 5). These are similar to the BIF Sill in appearance and general mineralogy; however, geochemical differences are apparent (to be discussed later).

Virginia Formation (VF)

The Virginia Formation is the uppermost unit of the Animikie Group (Fig. 5). Because the Virginia Formation is intruded and assimilated by the Duluth Complex, only the lowermost 400 feet (at most) are preserved within the study area. Rocks of the Virginia Formation are characterized by a sequence of well-bedded to massive-bedded argillite, fine-grained graywacke and siltstone, with minor interbeds of graphitic argillite, calc-silicate, and chert. Rare interbeds of marble and diopside-rich beds are also present in the Virginia Formation in the Babbitt deposit area (Severson and Barnes, 1991).

These rocks exhibit a granoblastic texture in close proximity to the Duluth Complex. They contain variable amounts of plagioclase, orthopyroxene (Opx), cordierite, biotite and quartz, and minor to trace amounts of graphite, sulfides, ilmenite, hornblende, apatite, and staurolite. Mineralogy varies due to the initial differences in bulk composition of the protolith. In general, cordierite content increases toward the contact with the Complex. Unique submembers of the
Recrystallized biotitic argillite (RXTAL) - Scattered within the Virginia Formation are thin (<2 feet) to thick (100-150 feet) zones/patches that consist of a totally recrystallized metasedimentary rock. Bedding planes are completely obliterated, and the rock contains medium-grained biotite flakes that are arranged in a decussate manner. At first glance, this decussate texture gives the rock an igneous appearance, and it has often been improperly classified as a Duluth Complex rock. However, the presence of quartz and a granoblastic texture indicate that the RXTAL zones are part of the Virginia Formation. Also, whole rock chemistry indicates that these RXTAL zones are identical to 'normal-looking' Virginia Formation (Severson and Hauck, 1990). The RXTAL zones often contain inclusions of well-bedded siltstone that are inclined at numerous orientations. The inclusions appear to represent 'boudined' blocks of structurally more competent interbeds within a recrystallized matrix.

In drill core, recrystallization ‘fronts’ are often seen on the edge of the RXTAL patches. These ‘fronts’ are readily defined wherever bedding planes gradually ‘disappear’ (within a few inches) into RXTAL patches. This ‘front’ is often perpendicular to the bedding plane trend.

Bedded Pyrrhotite member (BDD PO) - Consists of a sulfide-rich, graphite-bearing argillite with conspicuous pyrrhotite laminae (0.5 - 3.0 mm thick) that are regularly spaced at 1-20 mm intervals. The BDD PO member is about 20-100 feet thick and is locally present within the bottom 50-200 feet of the Virginia Formation. Pyrrhotite laminae vary from planar to highly
contorted. Where the BDD PO member has been intruded and assimilated by the Complex, it is an excellent local source of sulfur for basal pyrrhotite-dominated massive sulfide mineralization, e.g., Serpentine and Dunka Pit Cu-Ni deposits (Zanko et al., 1994).

Paraconglomerate member - Locally present as inclusions within the Complex at the northeast end of the Dunka Pit (Plate II-A) is a matrix-supported conglomerate. The rock contains about 5% sedimentary clasts (intraformational?) that are well rounded and up to 8 inches across; locally the clasts are structurally elongated. Similar conglomeratic horizons have also been encountered in scattered drill holes as far west as the Dunka Road deposit (drill hole 26029).

VIRG Sill - At least two sills are present within the bottom 30-80 feet of the Virginia Formation (Fig. 5). These sills were first reported by Gundersen and Schwartz (1962) where they noted (p. 70) that the sills ‘... in general are dark gray and fine-grained, and in some places difficult to distinguish in hand specimen from the metamorphosed Virginia Formation, particularly where the latter is hornfelsic.’ Though these sills are well known to the mining community of the eastern Mesabi Range, descriptions of them are sorely lacking in most published material pertaining to the geology of the region. The sills are shown on the geologic map of Morey and Cooper (1977) but are inadequately described. Unaware of their existence, Severson (1991) describe at least two zones of unusual rock within the bottom of the Virginia Formation at the Babbitt deposit. He tentatively refers to these zones as Sill(?) units and note that they exhibit a mineralogy and chemistry that is vastly different than the surrounding Virginia Formation. These differences indicate that the Sill(?) units
of Severson (1991) are indeed the sills that had been described earlier by Gundersen and Schwartz (1962).

Major constituents of the VIRG Sills, in decreasing order, are: plagioclase (25-60%); orthopyroxene (10-35%); amphibole (10-25%); olivine (0-15%); biotite (trace to 5%); and clinopyroxene (trace; 40% locally), with trace amounts of sulfide (minute pyrrhotite drops), ilmenite, apatite, quartz, and minute Cr-spinel crystals within hornblende. The VIRG Sills possess a granoblastic texture that is locally diabasic (as does the BIF Sill). Because both the VIRG Sills and the Virginia Formation were metamorphosed by the Complex, the VIRG Sills (as well as the BIF Sill) may be early Duluth Complex intrusions (Logan Sill age?) that were subsequently metamorphosed by later intrusions of the Complex. Chemically, the VIRG Sill and BIF Sill are different entities (to be discussed later), and thus, they may be related to at least two different intrusive events.

MIDDLE PROTEROZOIC ROCKS

Nopeming Formation?

The Nopeming Formation, and the potentially correlative Puckwunge Formation, unconformably overlie the Lower Proterozoic rocks. Only two outcrop localities for the two formations exist: the Nopeming crops out just west of Duluth; and 130 miles away, the Puckwunge is intermittently exposed for about 25 miles along the international boundary in extreme northeastern Minnesota (Mattis, 1972). Both units are situated beneath, or near the base of, the North Shore Volcanic Group. They are characterized by a basal conglomerate overlain by quartzite/sandstone.

Several drill holes put down into the Complex within the vicinity of Dunka Pit (Fig. 1) intersected quartzite sequences that are present as either inclusions associated with basalt
inclusions, or as interbeds located near the base of a basalt inclusion. In almost all cases, the quartzite is located near the base of a group of basalt inclusions. Because the basalt inclusions are inferred to be correlative with the NSVG, and because the quartzite is situated near the base of the basalt inclusions, the quartzite sequences are tentatively assigned to the Nopeming Formation. Quartzite sequences were intersected in at least six drill holes, which are: PO-2, 8346, NM-14 (78 feet intersected), NM-25, NM-63 (12 feet intersected), and BI-75 (19 feet intersected). On Plate II-B, five of these holes are denoted by the term QTZ positioned adjacent to the hole. Cursory petrographic inspection indicates that the quartzites are characterized by a moderate to well-rounded, well-sorted, medium-grained quartz-rich (>99%) rock. Bedding planes are not readily evident in drill core.

Basalt

Scattered occurrences of fine-grained basaltic rocks are sporadically present in drill holes, railroad cuts, and outcrops from the Hoyt Lakes area northeastward to the Spruce Road deposit area. They are presumably correlative with the North Shore Volcanic Group (Keweenawan - 1.1 Ga) and have been described by: Bonnichsen (1972); Tyson (1976); Dunlavey (1979); Severson and Hauck (1990); and Severson (1991). These basalts are most often present as hanging wall inclusions within the Duluth Complex, but locally the basalts are in direct contact with the Virginia Formation. The latter occurs at the ’Erie Hornfels’ (section 18, T.59N., R.13W.) of Tyson (1976), and in drill hole RMC 65223 of the Peter Mitchell Mine (Fig. 1). The inclusions exhibit sharp to gradational contacts with the surrounding troctolitic rocks of the Complex. Typically the basalts are fine-grained, massive, and granular-textured. Zones with vesicles, consisting of plagioclase and/or pyroxene-filled ovoids up to 1.5 cm across, are locally present within the basaltic rocks, and thus, their identification is relatively straightforward. Occasional scoriaceous flow top zones (†
angular detrital quartz grains) are also present, but generally these are rare. In some cases, non-vesicular material logged as basalt in drill core may actually be inclusions of earlier chilled intrusive material of the Complex; however, this is a distinction that is next to impossible to differentiate in one-dimensional drill core. Overall, the rock contains varying amounts of plagioclase (40-60%), clinopyroxene (trace to 50%), orthopyroxene (trace to 50%), olivine (trace to 25%), inverted pigeonite (trace to 35%), and rare to trace amounts of ilmenite (no magnetite), pyrrhotite, chalcopyrite, and apatite. The basalts in the Serpentine Cu-Ni deposit commonly grade into medium-grained rocks, referred to as norite and norfel in Plate VIII-B. The term norfel refers to a fine- to medium-grained rock that contains local vesicles; it is a basalt that has been recrystallized to varying degrees. Norite refers to medium-grained decussate rocks that contain increased amounts of inverted pigeonite, but original textures are not preserved. Whole rock chemistry (to be discussed later) indicates that the basalt inclusions, and the immediately adjacent norite, are identical.

For the most part, the basalt inclusions are located well above (>1,200 feet) the basal contact of the Duluth Complex. However, within the Serpentine Cu-Ni deposit, basalt inclusions are located much closer to the basal contact (within 150 feet). This relationship is evident in the cross-sections of Martineau (1989), this report (Plate VIII-B), and Zanko et al. (in prep.). To the immediate north of Serpentine, drill hole RMC 65223 intercepts about 75 feet of basalt that is in direct contact with the Virginia Formation. In RMC 65223 the preserved Virginia Formation thickness, between the basalt and the BIF, is only 80 feet! From the above discussion, the Serpentine area is unique in that: 1) the Virginia Formation is anomalously thin and may have undergone extensive local erosion before basalt deposition; and 2) the basalt is present at, or very near, the basal contact of the Complex. Possibly the basalts were deposited in a localized valley (erosional unconformity?) that was eroded into the Virginia Formation prior to the Keweenawan.
It is interesting to note that inclusions of the Nopeming Formation (?) are also roughly present within this same anomalous zone.

Another feature that is unusual in the Serpentine area is that the basalt inclusions positioned closest to the basal contact contain thin interbeds of cordieritic metasediments that are remarkably similar to the hornfelsed Virginia Formation. At first, this presented a quandary in that the relationship of interbedded basalt and Virginia Formation could suggest that the basalts are similar in age to the Virginia Formation. On the other hand, these interbeds may have been derived from material that occasionally slumped in from the sides of a valley. If the slumped material was totally derived from a Virginia Formation protolith, it would be mineralogically similar to the Virginia Formation (only it had been displaced into a valley). The latter explanation is more likely because the relationship of basalt over thin Virginia Formation has only been found within the Serpentine area. This suggests extremely localized special conditions - which a basalt-filled valley within the Virginia Formation more aptly explains.

**CC-type Inclusions**

Inclusions of a strongly magnetic, fine-grained, granular rock of gabbroic composition are present in several drill holes in both the SKI and PRI. Because the drill core of these inclusions strongly resemble rock outcrops exposed in the Colvin Creek Hornfels area, described by Severson and Hauck (1990), it is designated as CC on the accompanying cross-sections of this report. The rock exhibits a granoblastic texture characterized by polygonal plagioclase that tend to meet at 120° triple point junctions. Clinopyroxene is generally the more dominant pyroxene. Olivine is locally present as oikocrysts. Hornblende is also locally present and forms reaction rims around oxides. Magnetite is the dominant oxide (5-30%). Green pleonaste, biotite, and apatite are present in trace amounts. Overall, the rock exhibits a massive appearance, but it may locally contain
plagioclase phenocrysts (up to 1.5 cm), ovoid plagioclase-filled wisps (vesicles?), and thin (< 1 cm) subparallel magnetite-rich bands (beds or “sweatouts?”) displaying shallow dips of $10^\circ E - 30^\circ E$ (from horizontal).

The protolith of the CC inclusions is somewhat perplexing. The rock locally contains features indicating a volcanic origin (plagioclase-filled wisps = vesicles?). However, some thick inclusions are massive and void of vesicles. In these cases, a volcanic origin is not readily evident, and the rock could represent inclusions of earlier-emplaced, chilled micro-gabbro. Also, modally bedded oxide horizons with adcumulus magnetite (and green pleonaste) are common within some of the inclusions (Severson, 1991). An excellent example of a CC inclusion with well defined magnetite laminae is in the top portion of drill hole NM-9 in the Dunka Pit area. Even though the inclusion is situated about 1,000 feet above the basal contact, Bonnichsen (1972 - Figure V-46) logged the inclusion as Biwabik Iron-formation.

The CC inclusions intersected in drill core are remarkably similar to some of the outcrops of the Colvin Creek Hornfels (CCH). The CCH was first described by Bonnichsen (1972), who concluded that the inclusion was a hornfelsed basalt of the North Shore Volcanic Group. Tyson (1976) looked at the CCH, as well as three other hornfelsed basalt inclusions, and concluded that the CCH was different than ‘typical’ basalt inclusions. He felt the CCH was an oxidized North Shore Volcanic basalt, and that the difference was due to weathering of the basalt prior to metamorphism. Severson and Hauck (1990) conducted reconnaissance mapping the area and found several mappable features that conflict with a ‘typical’ hornfelsed basalt protolith. They also mapped a near-vertical, 1,000 foot thick cross-bedded unit within the center of the CCH consisting of fine-grained plagioclase, augite, and magnetite rock but no quartz. The cross-bedded unit is overlain by coarse-grained, modally bedded gabbro and troctolite - the modal bedding in the intrusive rocks are subparallel to the bedding in the cross-bedded unit. Severson and Hauck (1990)
note that the exact origin of the CCH was not resolved. The CCH is being investigated by Patelke (in prep.). The current view of the CCH (Patelke, pers. comm.) is that it represents a package of volcanic, sedimentary, and micro-gabbro sills that are tilted to near-vertical. At the base of the CCH is a collection of thin, hot volcanic flows that were erupted near a volcanic center. These are covered by a 1,000 foot thick cross-bedded unit that is interpreted to be a reworked mafic tuff that was deposited via wind within a provenance-restricted collapsed caldera. Intruded into the base of the CCH are sill-like micro-gabbros that are apparently related to the nearby Powerline Gabbro.

The nature of the CC inclusions present in drill hole is far from resolved. These enigmatic fine-grained rocks have been called a variety of names that include: oxide micro-gabbro, basalt, and Biwabik Iron-formation (CC inclusions with magnetite bands). In order to avoid this conflicting assemblage of names, inclusions of fine-grained, strongly-magnetic, granular-textured, gabbroic-composition rocks are consistently referred to as CC inclusions in this report and in Severson (1991). Inclusions referred to as ‘basalt’ in this report exhibit a similar texture to the CC inclusions, but are always magnetite-poor relative to the CC inclusions. Both CC and basalt inclusions exhibit vesicle-like features and have common chemical signatures (Severson, 1991).

VIRG Sill

At least two sills are present within the lower portion of the Virginia Formation. They may be early Duluth Complex in age and are described in a previous section pertaining to Lower Proterozoic rocks (p. 27-28).

BIF Sill
The BIF Sill is present within the Biwabik Iron-formation and is described in the Lower Proterozoic section (p. 24-25).

**Duluth Complex**

The stratigraphic packages present within the Partridge River intrusion (PRI) and South Kawishiwi intrusion (SKI) are described later in this report (p. 51-103).

**Oxide-bearing Ultramafic Intrusions (OUI)**

Several late-stage pegmatitic ultramafic plugs and vertical bodies of OUI intrude the troctolitic rocks of the PRI, and to a lesser extent the SKI. The acronym OUI was first used by Severson and Hauck (1990) to designate cross-cutting pegmatitic bodies of dunite, peridotite, picrite, melagabbro, clinopyroxenite, and orthopyroxenite that had a high percentage of oxides. These bodies occur as either roughly spheroidal plugs with apophyses into the troctolitic rocks, or as steeply inclined tabular to lensoidal bodies. They occur both close to the basal contact, and up to 2,000 feet above the basal contact of the Complex. Severson and Hauck (1990) briefly describe several OUI bodies informally known as: Longnose; Longear; Section 17; Section 22; and Skibo. Small OUI bodies are also encountered: 1) at depth in the Wyman Creek and Babbitt deposit areas; and 2) high above the basal contact in the Dunka Road and Babbitt deposit areas (Severson and Hauck, 1990; Severson, 1991). The Water Hen intrusion (Fig. 1) is interpreted to be a pegmatitic OUI body that intrudes troctolitic rocks (Strommer et al., 1990). In almost all cases, the OUIs exhibit sharp contacts with the troctolitic rocks and are clearly younger. Several different rock types may be present in a particular OUI body. These rock types may either alternate randomly within an OUI body, or they may be distributed in a zoned fashion. Linscheid (1991) reports that the Longnose body is crudely concentrically zoned, with a dunite core grading outward and
downward through peridotite into pyroxenite. Internal contacts between the rock types vary from abrupt to sharp. Extreme grain size variations, consisting of alternating fine- and coarse-grained rocks, may also be present within a single rock type. These variations may indicate that the OUIs were emplaced during multiple magmatic pulses.

Oxide content in the OUIs is highly variable and ranges from 5-10% disseminated oxides to massive oxide lenses up to tens of feet thick. Ilmenite is generally present in much greater quantities than titanomagnetite. Some of the OUI bodies, especially within the Babbitt deposit area and in the SKI, do not contain >5% oxides, and thus, the designation of OUI is somewhat of a misnomer. However, the OUIs at the Babbitt deposit and within the SKI exhibit the same overall textures (pegmatitic) and the same intrusive relationships to the surrounding troctolitic rocks; therefore, the OUI term is retained. The OUI designator used on the plates of this report can be considered to be synonymous with coarse-grained to pegmatitic pyroxene-rich rocks and/or coarse-grained olivine-rich rocks that cross-cut the troctolitic rocks.

Petrographically unique to the OUIs in the SKI are coarse-grained to pegmatitic pyroxene that exhibits mutually sinuous to consertal grain boundaries. Olivine-rich rock types contain medium- to coarse-grained, subrounded, equant olivine grains that exhibit triple point junctions with other olivine grains. Hornblende is present as subhedral to euhedral, coarse-grained crystals. Petrographically unique to the OUIs are intercumulus plagioclase (<20%) and rare intercumulus calcite. Also present within the OUIs are minor amounts of biotite (<5%), coarse-grained apatite (up to 15% locally), oxides (typically ilmenite), and sulfide. Sulfide occurs as <1-2 mm round droplets consisting of pyrrhotite ± chalcopyrite. Graphite may also be locally present within the OUIs.

In most instances, the OUIs in both the PRI and SKI are associated with structural discontinuities or faults. For example, the Longnose, Longear, and Section 17 OUI bodies (Fig. 1)
are aligned along a northeast-trending fault (Severson and Hauck, 1990). The OUIs at the Babbitt deposit are aligned along a east-west trending direction that coincides with a magnetic high (Severson, 1991) and with an inferred fault (Hauck, 1993). Several near vertical OUI bodies are also associated with a north-trending fault referred to as the Grano Fault (to be discussed below). All these facts point to the local importance of structural conditions in the formation, and/or emplacement, of the OUI bodies.

In addition, many of the oxide-rich OUI bodies in the PRI are spatially associated with areas where the Biwabik Iron-formation is present at the basal contact and is in direct contact with the Complex. The Longnose, Longear, and Section 17 OUI bodies are spatially situated over an area where a window of BIF is present at the basal contact (Severson and Hauck, 1990). The OUI bodies associated with the Grano Fault are also spatially situated over an area where the Biwabik Iron-formation is in direct contact with the Complex. At depth in this same area, ultramafic rocks are also present at the basal contact and these rocks grade downward into the Biwabik Iron-formation. The basal ultramafic rocks are referred to as the Basal Ultramafic Unit (to be described later) and are mineralogically and texturally similar to OUIs. Overall, these spatial relationships suggest a genetic link of oxide-rich OUIs to areas where massive iron-formation assimilation occurred at the basal contact. In this manner, partial melts were derived from assimilated iron-formation and were emplaced into structurally prepared zones to form OUIs. A major problem with this mode of origin is the source of titanium because the Biwabik Iron-formation does not contain an appreciable amount of titanium. This suggests that an iron-rich melt, derived from assimilated iron-formation, would have had to act as a ‘titanium trap’ during OUI genesis. In the Dunka Pit area the Biwabik Iron-formation contains much higher than normal Ti and V concentrations when it is in direct contact with the Complex (Muhich, 1993a, 1993b). This Ti enrichment indicates that there was some metasomatic transfer of Ti from the Complex across the contact into the iron-formation.
Whether this process accounts for the extremely high Ti concentrations in the OUIs has yet to be demonstrated.

In summary, the OUIs are associated with structural discontinuities that appear to have been important to OUI emplacement. Intrusion and assimilation of the Biwabik Iron-formation at depth may have produced partial melts that migrated upward along fault zones to produce some of the OUIs. The OUIs may have also formed in structural zones via a metasomatic replacement mechanism. This type of origin has been suggested for iron-rich ultramafic plugs within the Bushveld Complex (Schiffries, 1982; Viljoen and Scoon, 1985). It involves infiltration metasomatism, which is the upward-streaming of intercumulus fluids derived from within the crystallizing cumulate pile. Future detailed investigation of the Duluth Complex OUIs should be directed at determining which of the above processes, or a combination of them, is responsible for OUI genesis.

The OUIs are intimately mixed with late granitic/felsic intrusives within the vicinity of the Grano Fault. At this locality their origins may be interrelated. These granitic rocks are discussed in the following section.

Granitic/Felsic Intrusives

Steeply inclined lenses of coarse-grained to pegmatitic granitic/felsic rocks also intrude the troctolitic rocks. These granitic rocks are widely scattered throughout both the PRI and SKI and generally occur as very thin near-vertical veins. However, they are especially common, and voluminous, in the vicinity of the Grano Fault (Fig. 1) where late intrusive granitic lenses, as well as OUI lenses, are intersected in at least 14 drill holes that outline a zone that is situated within and to the immediate west of the fault trace (Plate 1a). The zone is about 2,000 feet wide at its southern end (Babbitt area) and pinches out to the north (Serpentine area).
Within the Grano Fault zone, a wide variety of leucocratic and melanocratic granitic rocks are intimately associated with subvertical OUI lenses (dominantly pyroxenite). All rock types often alternate within a single drill hole, e.g., drill hole B1-431 on Plate VIII-A. Using the classification scheme of Streckeisen (1976), a wide spectrum of rock names can be applied to the granitoid rocks that include: syenite (locally consists of a vuggy 'red rock' variety), granite, monzonite, monzodiorite, melanomonzodiorite (or hornblendite), diorite, and quartz diorite. The granitic rocks contain highly varying amounts of plagioclase (0-70%), K-spar (0-99%), hornblende (0-70%), clinopyroxene (0-10%), orthopyroxene (0-20%), quartz (trace-55%), biotite (trace-10%), chlorite (trace-30%), olivine (rare; locally up to 15%), and apatite (up to 15% locally in the melanocratic variety). Minor amounts of ilmenite (with rare composite magnetite), sulfide (pyrrhotite > chalcopyrite), and interstitial calcite are present locally. Locally the granitic rocks are: 1) granophyric - characterized by vermicular K-spar and quartz; 2) pegmatitic - generally quartz-rich (+ quartz veins); or 3) vuggy - the vugs are often filled with terminated quartz crystals. The contacts between this wide spectrum of rock names, and the OUIs, range from sharp to gradational. A good example of this can be seen in the top half of drill hole B1-155 where an orthopyroxenite grades into a hornblendite, which in turn grades into a hornblendite with 20% vermicular K-spar/quartz blebs. Interestingly, Martineau (1989) shows this same zone in one of his cross-sections (Fig. 10, p. 131) as an inclusion of Biwabik Iron-formation! Throughout the plates of this report, the late cross-cutting granitic/felsic lenses are designated by logging terms of: gr - for granitic rocks of a wide variety; hnbl gr - for hornblende-bearing granitoid; hnbl - for hornblendite (or melanomonzodiorite according to the classification of Streckeisen (1987)); and hyb - for hybrid rocks. Bonnichsen et al. (1980) referred to this same class of granitic/felsic rocks and OUIs as 'hybrid intrusive rock.'
Because lenses of OUI and granitic rocks are exceedingly common to the immediate west of a major north-trending fault, this fault is informally referred to as the Grano Fault in this report. The source magma for these late intrusive bodies may be either: 1) partial melts derived from assimilated footwall rocks in contact with the Complex that were expelled upwards into structurally prepared zones; 2) expelled, highly evolved intercumulus material derived from within the cumulus pile of troctolitic rocks; or 3) a combination of #1 and #2. The Biwabik Iron-formation is the footwall rock in the immediate vicinity of the Grano Fault (Plate II-A). Immediately east of the fault, granitic rocks of the Giants Range Batholith are in direct contact with the Complex. Both of these footwall rocks could have been assimilated and undergone partial melting at depth. The resultant partial melt could have been injected upward along sympathetic fault zones immediately west of the Grano Fault. Regardless of the source of the granitic and OUI bodies, pre-existing structural conditions are a dominant prerequisite for their genesis.

The Grano Fault is located roughly at the inferred contact between the PRI and SKI. Overall, the late cross-cutting granitic/felsic and OUI lenses associated with the Grano Fault exhibit two features that crudely indicate that the PRI was intruded before the adjacent SKI. These features are: 1) when present within the PRI, the late cross-cutting lenses are restricted to the immediate west of the fault trace (away from the SKI); and 2) the zone that contains these late lenses tapers off to nonexistence within the SKI. In both instances, the late lenses are restricted solely to the PRI rather than the SKI. This implies that the PRI had already been emplaced and crystallized before the late lenses were injected. The ‘injection event’ may have been established when the SKI intruded alongside the PRI. These theories only crudely hint that the PRI is older and was intruded by the SKI. Other lines of evidence, to be discussed later, also suggest that the PRI is older than the SKI.
Dikes

Fine-grained basaltic dikes that cross-cut the rocks of the PRI and SKI are shown on the geologic map of Morey and Cooper (1977). Because field mapping was not a part of this investigation, these dikes are not shown on the Plates of this report. Additional dikes are documented by: Severson (1991); Hauck (1993); and Severson (in prep.). Within the Bathtub area of the Babbitt deposit, at least two parallel northwest-trending basaltic dikes are intersected by drill holes. These dikes cut both the footwall and troctolitic rocks. They exhibit chilled margins with the troctolitic rocks, and the troctolitic rocks are locally brecciated adjacent to the dikes. To the north, the same dike trend is present within the pit exposures of the Peter Mitchell Mine. At this locale, at least three subparallel dikes are present, and one of the dikes is intruded into a fault zone. Severson (in prep.) found a total of five dikes cutting the Biwabik Iron-formation in the Peter Mitchell Mine. Another dike is reported in the drill logs of the Spruce Road deposit (Plate XV-B). Because the dikes in the Bathtub area are chilled against troctolitic rocks of the Complex, a late-to post-Duluth Complex age is indicated.

PLEISTOCENE DEPOSITS

A veneer of glacial material of highly variable thickness covers much of the PRI and SKI. The overburden was not cored nor logged in detail within the area of investigation, thus little is known of its characteristics. The depth of overburden in drill hole varies from <1 foot to 132 feet. Overall, the overburden is less than 20 feet deep, with a few exceptions. Immediately east of Dunka Pit, drill holes put down on the west half of an exceptionally flat area known as Glacial Lake Dunka (Winchell, 1901) in sections 10, 11, 14, and 15 encounter 50-90 feet of overburden. Also in the same area (north halves of sections 10 and 11), drill holes collared in the Vermilion Moraine (Lehr and Hobbs, 1992) encounter 65-132 feet of overburden. These holes indicate that the depth to ledge is
anomalously high in the vicinity of Glacial Lake Dunka. Lastly, anomalous high overburden thicknesses are associated with the Grano Fault in section 28. There, a thin north-trending trough is positioned over the fault trace and exhibits overburden depths of 50-100 feet deep in several drill holes. This indicates that some structural zones associated with the Grano Fault were easily quarried and filled in with glacial material during the Pleistocene.
REGIONAL GEOLOGY - DESCRIPTION OF FAULT ZONES

Several faults are mapped within the SKI and in the footwall rocks to the north of the SKI (Green et. al., 1966; Morey and Cooper, 1977; Foose and Cooper, 1981; Holst et. al., 1986). Not all of these faults are shown on the plates of this report (Plates I, II, and XV). Only a select number of faults are shown, and these, in the author's opinion, are the most strongly definable faults. Specific criteria used in determining which faults would be shown include: 1) the fault must exhibit definable offset in either the basal contact or the footwall rocks; 2) the fault must demonstrate an offset of igneous units; 3) the surface trace of the fault is correlative with a strong aeromagnetic lineament (low); and/or 4) a topographic lineament (low) is associated with the fault trace (only very strong topographic lineaments were used). All of the faults in this report meet one or more (usually two or more) of the above criteria. Because little time was spent defining topographic and aeromagnetic lineaments, not all potential faults are portrayed. The faults and their relationship to the contoured basal contact of the Duluth Complex are shown in Plates II and XV.

Faults within the Dunka Pit area were initially mapped by Bonnichsen (1968). Additional faults were also located and described in the Dunka Pit area by Holst et al. (1986). They assigned ‘B-number’ designators to these faults (B-20 through B-30). These same faults are shown on several maps and cross-sections of this report where they are also referred to by the same designator as Holst et. al. (1986). Because most of the faults exhibit only minor amounts of offset, they cannot be traced with certainty to the south into the adjacent Duluth Complex. This is also true of faults within the Peter Mitchell Mine. There, most of the faults are ‘scissors-type’ faults in that they exhibit increasing amounts of offset toward the Complex. Overall, little is known about the faults except for their relative motion. However, three of the faults are unique and deserve special attention; these faults are described below.
GRANO FAULT

The Grano Fault (Plate I-A) is a major north-trending fault situated near the boundary between the SKI and the PRI. At its southern end (sections 28 and 33, T.60N., R.12W.), the Grano Fault is defined by four features: 1) a steep drop in the basal contact to the southeast (Plate I-B); 2) the Virginia Formation is footwall to the Complex west of the fault, and the BIF is footwall to the east of the fault; 3) abundant vertical lenses of late granitic rocks are common to the fault zone; and 4) the depth of glacial overburden dramatically increases within the fault zone. It is difficult to determine the exact amount of displacement along the Grano Fault since the top portion of the BIF has been removed east of the fault during intrusion of the Complex. However, assuming that the BIF is about 400 feet thick and dips at about 10\textdegree-15\textdegree, offsets of 100-250 feet, down to the east, are indicated. Further south of this area, the continuation of the fault trace is expressed as a well defined topographical lineament in section 9, T.59N., R.12W.

At its northern end, the Grano Fault is present in the Serpentine Cu-Ni deposit. Correlation of drill hole data (Zanko et al., in prep.) indicates that the basal contact and the top of the BIF have been offset by about 10-30 feet, down to the east, along the trace of the fault. The diminished amount of relative motion along the Grano Fault, from south to north, indicates that it is a ‘scissors type’ fault with increased movement toward the interior of the Complex. No late granitic lenses are associated with the fault at Serpentine. North of Serpentine, the fault could not be traced with certainty into pit exposures of the Peter Mitchell Mine. This may be because the fault either terminates against a northeast-trending fault present in the mine area (Severson, in prep.), and/or there is continued diminished offset to the north along this ‘scissors type’ fault. Note also that the late granitic lenses, for which this fault is named, diminish in occurrence and eventually ‘disappear’ in a south-to-north direction.
Activation of the Grano Fault appears to have been initiated before the PRI and SKI were emplaced. This relationship is indicated by an increase in the number of BIF sills (Logan Sill age?) within the Serpentine area. In the following discussion, it is important to remember that throughout the entire area of this investigation, the BIF contains only one BIF Sill, and that it is present within the middle of BIF submember C (Fig. 5). However, a select group of drill holes within the Serpentine area intersected numerous sills within BIF submembers A through C (Zanko et al., in prep.). For the sake of discussion these sills within the BIF, not including the typical BIF Sill, will be referred to as EXTRA BIF Sills. Curiously, drill holes with more than four EXTRA BIF Sills are spatially restricted to a 850 foot wide zone that trends north-south and straddles the Grano Fault (Zanko et al., in prep.). This relationship indicates that some movement along the Grano Fault occurred during BIF Sill emplacement. During emplacement, the BIF Sill appears to have bifurcated into dilatant zones adjacent to the Grano Fault, and thus, it was emplaced into additional submembers of the BIF to form the EXTRA BIF Sills. Note also that the typical BIF Sill is present at the same stratigraphic position within the BIF (within the middle of submember C) on both sides of the Grano Fault. This illustrates that any movement along the fault could not have taken place before the BIF Sill was emplaced (thus, the BIF Sill does not "jump" stratigraphic position across the fault). A possible scenario for this history is presented in Figure 6. Note that the BIF Sill is portrayed as bifurcating/intruding upward to produce the EXTRA BIF Sills. The VIRG Sill could just as easily have intruded downward to produce the same result. Chemical analyses (discussed later) indicate that the EXTRA BIF Sills are more closely related to the VIRG Sill than they are related to the BIF Sill.
The above observations indicate that Grano Fault movement was initiated at about the same time as either BIF Sill or VIRG Sill emplacement (Logan Sill age?). Continued motion (reactivated) along the fault occurred during and after intrusion of the PRI and SKI as indicated by the offset basal contact across the fault, and the presence of abundant granitic/felsic lenses that intruded the troctolitic rocks adjacent to the fault.
FAULT B-29

Fault B-29 is a north-trending fault exposed within the Dunka Pit mine (Plate II). Where exposed, it juxtaposes BIF, west of the fault, against SKI rocks to the east of the fault. The fault is near-vertical, and the indicated relative motion (approximately 100 feet) is down to the east. The age of the fault is not as easily determined, but faulting appears to have been initiated before emplacement of the SKI. Both the BIF and SKI rocks are slickensided in the immediate vicinity of the fault, indicating that the fault was reactivated after SKI emplacement.

A pre-SKI age for Fault B-29 is suggested by several lines of evidence that are schematically portrayed in Figure 7. First, the BIF exhibits a gradational change in character (texture and composition) from well-bedded iron-formation into a troctolitic rock with magnetite bands toward the fault zone. This compositional change is represented by a gradational replacement of the silicate/chert beds by medium- to coarse-grained plagioclase ± augite toward the SKI. Eventually, only the magnetite laminae are present within a plagioclase-olivine-augite rock, and it is difficult to call the rock either BIF or SKI. These magnetite laminae do not persist very far into the SKI (~1-2 feet?). Second, to the immediate west of the fault, the BIF contains anomalously high amounts of titanium due to the transfer of Ti across the fault (Muhich, 1993a; 1993b). This overall gradational change in character (compositional and textural) in the BIF across the fault zone indicates that the fault is pre-SKI in age. Third, drilling into the BIF on the west side

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Figure 7. Schematic diagram of gradational changes in the BIF relative to Fault B-29 (at the northern end of the Dunka Pit). Not to scale.
of the fault intersected a few lenses of SKI rocks that are present at various stratigraphic levels within the BIF. These lenses do not persist very far into the BIF. Fourth, exposures on the east side of the fault consist of SKI rocks that contain abundant Virginia Formation inclusions rather than BIF inclusions. The Virginia Formation inclusions consist of elongate-tabular inclusions of well-bedded argillites and pod-like inclusions of calc-silicate. All of the inclusions are completely surrounded by a 1-1.5 cm thick rind of white chalcedony. Such rinds have not been found anywhere else within the Complex. The rinds suggest that extreme silica contamination of the magma occurred on the east side of the fault wherever the SKI was in direct contact with the BIF. Finally, on the east side of the fault is a large exotic inclusion (>5 x 5 feet) of BIF submember B situated within the SKI (Plate I-A). This inclusion either fell into the magma from the west side of the fault, or ‘floated-up’ in the magma on the east side of the fault.

Altogether, this evidence suggests that the majority of offset occurred along Fault B-29 before the SKI was emplaced. It appears that the Virginia Formation, originally present on the east side of the fault, was easily intruded and assimilated along bedding planes by the SKI. However, when the magma reached the ‘wall of BIF,’ present on the west side of the fault, intrusion was abruptly halted, and only a minor portion of the magma continued to intrude along BIF bedding planes. In the vicinity of Fault B-29, the BIF became enriched in Ti, which was transferred across the fault/contact. Concomitant Si contamination occurred in the SKI to produce the chalcedony rinds around the Virginia Formation inclusions. Reactivation of the fault after solidification of the Complex produced slickensides in both the BIF and SKI in the immediate vicinity of Fault B-29. The relative amount of motion on Fault B-29 prior to intrusion of the SKI can not be determined with the present data.

Fault B-29 is extended further to the south of the pit exposures in this investigation based on drill hole correlations (Plates I and II). Several ‘horsetail’ splays are also indicated by additional
offsets in drill hole correlations. The fault, and its splays, are shown in the Dunka Pit cross-sections of this report (Plates VI-A, IX and X). They are expressed as: 1) offsets in the basal contact and footwall rocks; 2) offsets in the SKI troctolitic stratigraphy; and 3) highly sheared, slickensided, and serpentinitized troctolitic zones intersected in drill hole. The latter two features illustrate that some motion (reactivated?) occurred along Fault B-29 after the troctolitic rocks were solidified. The amount of motion indicated by offset SKI units is about 200-400 feet.

In summary, Fault B-29 was activated before emplacement of the SKI. Originally, BIF and Virginia Formation were juxtaposed across the fault. During SKI intrusion, the Virginia Formation was assimilated and effectively 'removed' leaving the BIF in direct contact with the SKI. At this time, Ti was metasomatically transferred across the fault from the SKI into the BIF, and Si was transferred in the opposite direction. At some later point in time, the fault was reactivated, and the troctolitic rocks of the SKI were offset. About 100 feet of motion occurred at the northern end of the fault (in the pit area), and 200-400 feet of relative motion occurred at the southern end of the fault (in the drilled area). This evidence indicates that Fault B-29 is a 'scissors-type' fault.

On Plate IX-B is an unexplained phenomena. Fault B-29 is intersected in drill hole D-13 at about 249-343 feet. Here the fault zone is characterized by strongly brecciated and serpentinitized broken drill core that alternates between norite (?) and graphite-bearing metasedimentary rocks (BDD PO Unit?). Toward the top of the fault zone is a four foot thick inclusion of relatively fresh BIF (266-270 ft.). What makes this BIF inclusion so unique is that it was intersected above Virginia Formation hornfels inclusions. Also unique to this BIF inclusion is that it is positioned approximately 200-300 feet above the top of the footwall BIF. In other words, the BIF inclusion is too high off the floor of the SKI. Exactly how this inclusion came to be positioned so high up above the basal contact is unknown. It may represent a small BIF piece that was caught up in the fault zone.
BIRCH LAKE FAULT

The inferred presence of the Birch Lake Fault is defined by a zone wherein drill holes commonly encounter either: massive sulfide and disseminated sulfide mineralization within the Giants Range Batholith footwall rocks (Fig. 4), or late cross-cutting granitic/felsic lenses that intrude the troctolitic rocks of the SKI. Evidence pertaining to the amount of offset associated with this fault are meager due to the distribution of widely scattered drill holes. A sense of motion of down to the east is indicated. Since the Birch Lake Fault is inferred from scattered drill hole information, only a general location is shown (Figs. 4 and 55). Interestingly, the fault trends through the Birch Lake Deposit where significant PGEs are associated with troctolitic and ultramafic rocks located near the base of the SKI.
INTRODUCTION

The PRI consists of at least seven major igneous units that are intersected in drill holes and are correlated along a 15-mile strike length that extends from the Wyman Creek Cu-Ni deposit to the Babbitt Cu-Ni deposit (Fig. 1). These seven stratigraphic igneous units are referred to as the Partridge River Troctolite Series (PRTS). The distribution and stacking arrangement of these units are schematically portrayed in Figure 8. Because the PRTS will later be compared to the igneous stratigraphy of the SKI, a brief description of the PRTS is necessary. More detailed descriptions of the PRTS are in Severson and Hauck (1990) and Severson (1991). A description of the PRTS, from the base upwards, follows.

UNIT I - SULFIDE-BEARING AUGITE TROCTOLITE AND TROCTOLITE

The lowest troctolitic unit of the PRTS consists dominantly of intermixed troctolite and augite troctolite that grades to olivine gabbro. Most of the unit is sulfide-bearing. Augite troctolite is the dominant rock type in the bottom half of Unit I, but it is also locally common in the top half of Unit I. Minor, laterally discontinuous ultramafic horizons (olivine-rich rocks) are scattered throughout the entire thickness of Unit I. The overall grain size is highly variable in Unit I and ranges from fine (＜1 mm) to pegmatitic (＞10 mm). Unique to Unit I are extreme variations in modal mineral percentage and average grain size; both change rapidly over zones from a few feet to tens of feet. Due to this heterogeneous texture, numerous internal contacts divide Unit I into several subunits that cannot be correlated from drill hole to drill hole. Thus, Unit I is a mixture
**Figure 8.** Generalized stratigraphy of the Partridge River Troctolite Series. The stratigraphy of the South Kawishiwi Troctolite Series within the Duce also included for comparison.
of various troctolitic subunits that are probably related to continuous magma replenishment. The thickness of Unit I is highly variable (150 to 1,570 feet thick) due to a nearly horizontal top and a divergent southeast deepening base.

Hornfels inclusions of Virginia Formation are most commonly present within Unit I. The inclusions vary from one inch to over 275 feet thick. Rock types are the same as those present at the basal contact. At the Babbitt Cu-Ni deposit, the largest hornfels inclusions (up to 2,400 x 3,200 feet across) are present in the Local Boy area where several raft-like inclusions are stacked above each other. The configuration of these inclusions suggests that Unit I was intruded along the bedding planes of the Virginia Formation in repeated pulses, coupled with subsequent assimilation of the country rocks.

Near the basal contact and surrounding hornfels inclusions, the intrusive rocks have undergone sufficient contamination, and norite is often the dominant igneous rock type. Norite describes generally fine-grained rocks that contain more hypersthene relative to olivine or augite. The thickness of norite intervals within Unit I is extremely variable—less than one foot to tens of feet. Even though norite is commonly present adjacent to hornfelsed sedimentary footwall rocks, there are several cases where troctolitic rocks and footwall rocks are in direct contact. When present, the norite generally exhibits a gradational contact with the troctolitic rocks and a gradational to sharp contact with the metasedimentary rocks.

The top of Unit I is defined on the basis of four criteria, of which, all or only one are present in a particular drill hole. These criteria include: 1) decrease in sulfide content upwards into sulfide-free rocks; 2) appearance of a persistent ultramafic horizon(s) that marks the base of overlying Unit II (or Unit IV in the Babbitt deposit area); 3) presence of semi-persistent large hornfels inclusions of Virginia Formation in the Local Boy area of the Babbitt deposit; and 4) presence of a semi-persistent, coarse-grained anorthositic troctolite in portions of the Babbitt deposit area.
UNIT II

Unit II is highly variable along its strike length. In the Wyman Creek area, it is characterized by a 20-40 foot thick picrite and/or olivine-rich troctolite overlying sulfide-bearing troctolites of Unit I. Toward the east, Unit II is characterized by abundant cyclic units of troctolite grading downward into picrite-peridotite-dunite layers in the Wetlegs Cu-N deposit; the rocks are generally sulfide-poor. Another lateral change toward the east occurs in the Dunka Road Cu-Ni deposit. There Unit II consists of sulfide-poor, homogeneous-textured troctolite with a persistent ultramafic base (picrite to peridotite). The same rocks characterize Unit II at the Babbitt Cu-Ni deposit; however, Unit II is only present in the southwest portion of the deposit. Sedimentary hornfels inclusions are fairly common within Unit II. Because Unit II exhibits numerous lateral changes, it can be considered to be heterogeneous overall.

UNIT III

Unit III is the major ‘marker bed’ of the PRTS in the Wetlegs, Dunka Road, and southwestern Babbitt Cu-Ni deposits. This unit is fine-grained (1-2 mm) and characterized by troctolitic anorthosite to anorthositic troctolite. The rock consistently grades into plagioclase-rich and olivine-rich patches that give the drill core an overall mottled-texture. This mottled appearance is due to very coarse (up to 3 cm) olivine oikocrysts that are irregularly distributed throughout the rock. The mottled-texture and fine-grained nature makes Unit III unique relative to all the other units of the PRTS. It is readily recognizable in drill core and easily correlated between drill holes, thus making Unit III an excellent marker bed. The coarse-grained olivine oikocrysts are found exclusively in Unit III and in thin intervals within Unit VII (inclusions of Unit III). The thickness of Unit III is highly variable and ranges from 135 ft. to over 850 ft. thick. Unit III is absent in the
Wyman Creek deposit and pinches out within the Babbitt deposit. In the southeastern portion of the Babbitt deposit, Unit III is present as discontinuous lenses within a thickened Unit I.

UNIT IV

Unit IV is characterized by thick intervals of homogeneous-textured troctolite and/or augite troctolite, which locally grades to olivine gabbro. Unit IV has a semi-persistent ultramafic horizon at its base. Due to its semi-persistent occurrence, the ultramafic horizon is informally termed the ‘± Picrite’ in the Babbitt deposit. The top of Unit IV is generally gradational into the overlying Unit V.

UNIT V

A homogeneous-textured, medium- to coarse-grained, anorthositic troctolite characterizes Unit V. Local gradations into plagioclase-rich (65-70%) troctolite, troctolitic anorthosite, augite troctolite, and olivine gabbro are present within restricted portions of Unit V. Minor inclusions of hanging wall rock first appear in Unit V at the Babbitt deposit. The bottom contact of Unit V is gradational into Unit IV, and the top contact is sharp against an ultramafic horizon that marks the base of overlying Unit VI. At the Wyman Creek deposit, the distribution of Unit V in drill holes suggests a downcutting relationship into Units I and II. This relationship indicates that Unit V is later than, and intrusive into, the lower units of the PRTS.

UNITS VI AND VII

The two uppermost units of the PRTS are remarkably similar, and thus they are both described in this section. They are present only in the top portions of deep drill holes put down into the Wetlegs, Dunka Road, and Babbitt deposits. Both units are characterized by homogeneous-
textured, medium- to coarse-grained troctolite and/or anorthositic troctolite, with minor augite troctolite and troctolitic anorthosite. Both contain: 1) a basal ultramafic horizon(s); 2) internal, minor, laterally discontinuous ultramafic horizons; 3) modally bedded adcumulus magnetite horizons (only in the Babbitt deposit); and 4) inclusions of both Unit III and hanging wall rocks. Due to these similarities, actual unit assignment to either Unit VI or VII is difficult unless the drill hole has penetrated a lower marker bed, and the hole is hung and correlated accordingly. Outcrop mapping indicates that other additional units are present above Unit VII. These units are apparently similar to Units VI and VII in that they consist of homogeneous-textured troctolites with basal ultramafic members. Because they have not been intersected in drill holes, they will not be discussed.

**BASAL ULTRAMAFIC UNIT**

The Basal Ultramafic Unit is a new addition to the PRTS that is defined in this investigation. The Basal Ultramafic Unit (BU Unit) is located at the basal contact of the PRI in an area where the Biwabik Iron-formation is the footwall rock rather than the Virginia Formation (Fig. 8). In this regard the BU Unit is a submember of Unit I that is spatially restricted to small area in the extreme eastern portion of the PRI. It is present in at least five drill holes in the southeastern portion of the Babbitt deposit. On Figure 8, the BU Unit is within the "transition zone" of the PRI.

The BU Unit is characterized by an upper picrite-peridotite zone (40 to 135 feet thick) that grades downward into a lower orthopyroxenite zone (0 to 22 feet thick). The upper zone consists of alternating troctolitic and ultramafic horizons; oxide-bearing picrite and peridotite are the dominant rock types. Massive oxide horizons, up to 19 feet thick, are common within the upper zone. Within the massive oxide horizons, titanomagnetite is dominant with minor ilmenite (composite grains) and green pleonaste. By contrast, either composite ilmenite-magnetite or
composite magnetite-ilmenite grains are present in the surrounding ultramafic horizons. Minor orthopyroxenite horizons are also present within the upper zone, and these zones increase in thickness and abundance with depth until they are the dominant rock type of the lower zone. With depth, the lower zone orthopyroxenites either grade into, or are in sharp contact with, the Biwabik Iron-formation. Often the orthopyroxenite and adjacent BIF are very similar in appearance. Some of the zones logged as pyroxenite could actually be recrystallized BIF. The BIF is characterized by a massive-bedded, medium- to coarse-grained orthopyroxene-rich rock, with occasional chert and/or magnetite-rich beds. The gradational change from the lower orthopyroxenite zone of the BU Unit to BIF is often very subtle, and the actual contact between the two is arbitrarily chosen in some drill holes. Also, in some drill holes the lower zone is absent, and the upper zone exhibits a gradation with depth into fayalite-rich BIF with minor quartz and occasional beds of chert and magnetite.

The gradational contact of the BU Unit with the BIF suggests that a combination of assimilated BIF and local contamination of the melt at the basal contact were important in the genesis of the BU Unit.

**GENERAL SUMMARY OF THE PRTS UNITS**

All units of the PRTS have shallow dips of 10E-20E southeast toward the axis of the rift. Most of the upper units (III through VII) are texturally homogeneous and are floored by ultramafic horizons (picrite-peridotite). The ultramafic horizons generally exhibit modally graded tops and sharp bases, indicating crystal settling. The ultramafic base of these units indicates that: 1) each troctolite unit was intruded sill-like as a single magmatic pulse and crystallized as a single unit; or 2) each ultramafic member represents the inception of episodic magma injection that crystallized more primitive ultramafic layers before mixing with the resident magma. By contrast, Units I and
II near the footwall are heterogeneous and contain abundant internal members and hornfelsed footwall inclusions. These characteristics indicate continuous magma replenishment and associated contamination from the footwall rocks. Though age relationships are uncertain, Unit I appears to have been intruded earliest along bedding planes of the Virginia Formation (as evidenced by the abundant inclusions and the heterogeneous nature). In contrast, the more homogeneous Units III through VII appear to have been emplaced into a progressively developed magma chamber with little interaction with the footwall rocks, except near the margins of the chamber.

Several horizons containing Pd-Pt mineralization have been defined within the PRTS at the Dunka Road deposit (Geerts, 1991; in prep.). Three horizons are present within Unit I, and a fourth horizon is locally present in the top of Unit VI. Of these four horizons, the most enriched one lies within the top 10-30 feet of Unit I, where an average of 1,200 ppb Pd+Pt is present (Red zone of Geerts, 1991). Elsewhere within the PRTS, Pd and Pt values as large as 11 ppm Pd and 8 ppm Pt have been obtained from the massive sulfide ore in the Local Boy area of the Babbitt deposit (Severson and Barnes, 1991).

MISCELLANEOUS FEATURES ASSOCIATED WITH THE PRI AND SKI

Deuteric Alteration

Within both the PRI and SKI, patches of deuteric alteration, or uralitization, are present in all the troctolitic units. Uralitization is characterized by replacement of interstitial Cpx by fine-grained mats of radiating bundles of chlorite, hornblende, actinolite, sericite, +tremolite, +calcite that commonly interpenetrate with adjacent plagioclase crystals. Also associated with this type of alteration are variably saussuritized plagioclase and moderately to strongly serpentinized olivine.

Chlorine Drops (Cl-drops)
Rust-colored fluid drops are locally present on the drill core surfaces and split core surfaces of several drill holes put down into both the PRI and SKI. Analysis of the drops indicates high chlorine content values up to 3,000 ppm (Dahlberg, 1987; Dahlberg et al., 1988; Dahlberg and Saini-Eidukat, 1991). Interestingly, these Cl-drops form soon after the drill core is exposed to atmospheric moisture via a deliquescent process. The drops are most common within some of the major ultramafic horizons and in some late Oxide-bearing Ultramafic Intrusions (OUI). Whole rock analyses of the ultramafic horizons and OUI bodies (Severson and Hauck, 1990; Severson, 1991; Severson, this report) indicate high Cl contents in both rock types regardless of whether the Cl-drops are present or not. Thus, the presence of Cl drops on drill core can be attributed to high Cl content within the rock and the rock’s ability to retain condensed moisture (much as CaCl is used to absorb humidity from the air). The Cl-drops have also been recognized in: disseminated sulfide zones; localized zones in the massive sulfide ore (Severson, 1991; Severson and Barnes, 1991); and within the top of the Biwabik Iron-formation (this study). Recent investigations indicate that the chlorine within the drill core is actually tied up in a newly discovered mineral referred to as hibbingite (Saini-Eidukat et al., in press). The rusty liquid Cl-drops, that are readily recognized as coatings on the drill core surface, are actually a breakdown product known as akaganéite (Saini-Eidukat et al., in press). The mechanism (post-cumulate?) that produced the initial high Cl content, and formed the mineral hibbingite, within the ultramafics is unknown. Dahlberg and Saini-Eidukat (1991) suggest that the rocks of the Duluth Complex were subjected to invasion by Cl-bearing solutions during or after serpenitization.

**NATURE OF THE PRI/SKI CONTACT ZONE**

Because the nature of the contact between the PRI and SKI was poorly understood, several drill holes in the extreme eastern portion of the PRI were relogged during this investigation. The
approximate contact between the PRI and SKI is shown on Plates I-A and II-A. This contact is roughly placed relative to the igneous stratigraphic packages that were intersected in specific drill holes. For example, drill holes to the immediate north and east of the contact intersect an igneous stratigraphy that is characteristic of the SKI. These holes are almost mirror images of holes drilled 3-6 miles away in the Dunka Pit area (Plate III) and will be discussed later. Conversely, drill holes immediately west of the contact intersected PRTS-type rock packages. These holes are correlated with drill holes put down in the nearby Local Boy area of the Babbitt Cu-Ni deposit (Severson, 1991) and are portrayed in: Plate III (the first six holes on the left side of the plate); Plate VI-A; and Plate VII. In viewing these plates, it is readily evident that many of the upper PRTS units begin to lose their identity, toward the contact of the two intrusions, and are not easily correlated between drill holes. This is especially true of the drill holes portrayed in Plates III and VII. These holes are located in the extreme eastern margin of the PRI in an area that is referred to as the ‘heterogeneous zone’ in Figure 9A. In Figure 9A, the ‘heterogeneous zone’ is positioned between the PRI and SKI
Figure 9. Nature and distribution of "heterogeneous zone" within the Partridge River intrusion. (though it is situated solely within the PRI), but it is also shown as wrapping around the northern margin of the PRI. This situation is indicated by the relationships portrayed in Plate VI-A, where the upper units of the PRTS become heterogeneous (north half of Plate VI-A) relative to the consistently correlative units present in the Local Boy area (south half of Plate VI-A). In summary, all of the upper units of the PRTS gradually become heterogeneous and indistinguishable from each other within the
‘heterogeneous zone’ of the PRI. Conversely, no ‘heterogeneous zone’ is present in the adjacent SKI. There, the stratigraphic package is astoundingly similar to the stratigraphic package intersected in drill holes located in the Dunka Pit area, 3-6 miles to the northeast.

The presence of dissimilar stratigraphic packages in the PRI and the SKI suggests that both intrusions represent separate emplacement events. This relationship, in turn, suggests that there should be a relative age difference between the two intrusions. The unique occurrence of the ‘heterogeneous zone’ at the margin of the PRI, but not in the adjacent SKI, provides a clue to this age difference. In viewing the overall PRI, broad zones of heterogeneous rock packages are restricted to Unit I, as well as the ‘heterogeneous zone.’ The heterogeneous nature of Unit I is probably related to its style of emplacement (repeated injections along bedding planes of the Virginia Formation) and, most importantly, the affects of contamination to the magma from assimilated footwall rocks. Likewise, the upper units of the PRI also become heterogeneous wherever they are in contact with the footwall rocks. This situation occurs along the northwestern exposed contact of the PRI in Figure 9A. In this area, the basal contact exhibits a steep upward rise (Plate II-A) that brings the upper PRTS units into direct contact with the Virginia Formation. This relationship suggests that the upper units of the PRTS become heterogeneous along the steeply inclined margins of the magma chamber where footwall rocks are being intruded and assimilated. This relationship is schematically illustrated in Figure 9B. By comparison, the ‘heterogeneous zone’ situated between the two intrusions signifies that the PRI may have once been in direct contact with the footwall rocks in this area as well (before emplacement of the SKI). The ‘heterogenous zone’ of this area is schematically shown in Figure 9C. Note that in Figure 9C the footwall rocks (Virginia Formation) are no longer present as they have been intruded, assimilated, and ‘removed’ by the SKI. However, the previous existence of footwall rocks in this immediate area is indicated by the presence of anomalously large, vertically-stacked, hornfels inclusions in the Local Boy area.
These large inclusions may have once been ‘attached’ to the footwall rocks at the margins of the PRI magma chamber (as is portrayed in Fig. 9B).

Because the ‘heterogeneous zone’ appears to have formed adjacent to footwall rocks at the margins of the PRI, then the PRI and SKI should still be locally separated by a ‘curtain’ of footwall rocks. This ‘curtain’ of footwall rock is still present between the two intrusions in section 29 (T.60N., R.12W.). Structure contours of the basal contact (Plate II-A) show that the base of the PRI rises steeply toward the north in this area, and that some of the drill holes are actually collared in the footwall Virginia Formation. To the immediate north of this area, the basal contact rapidly drops off, and rocks of the SKI are intersected in drill hole. Thus, the ‘curtain’ of footwall rocks that separates the PRI and SKI is still locally preserved. Because this ‘curtain’ disappears to the south in the area of Figure 9C, it must have been intruded, assimilated, and ‘removed’ by the later SKI. Only the ‘heterogeneous zone’ of the PRI remains. This zone formed by contamination of magma in direct contact with footwall rocks at the margins of the PRI magma chamber.

In addition, there are other indications that the PRI is older than the SKI. First, inclusions of Unit III-type rocks of the PRI are present within the SKI to the immediate northeast of the ‘heterogeneous zone’ (Plate III - drill holes B1-64 and B1-432). This situation suggests the PRI was emplaced and cooled before intrusion of the SKI. Second, a ‘heterogeneous zone’ analog is not present within the SKI at the contact between the PRI and SKI. If the SKI were younger than the PRI, then the lack of a ‘heterogeneous zone’ in the SKI could be the result of igneous rock intruding up ‘against’ earlier igneous rock. In this manner, the effects of contamination by assimilation would be minimized, and no ‘heterogeneous zone’ would be produced in the SKI. Third, hornfels inclusions of footwall rocks are more voluminous in the basal units of the PRI than they are within the basal units of the SKI. This implies that the PRI was initially intruded into ‘cold’ footwall rocks; whereas, the SKI was intruded later into ‘warm’ footwall rocks. Assimilation of the ‘warm’
footwall rocks by the SKI was apparently more complete. Last, late OUIs and late granitic/felsic rocks associated with the Grano Fault are restricted to the PRI, even though the fault trends through both intrusions. This suggests that only the PRI had been emplaced prior to the event that produced the late granitic/felsic bodies along the Grano Fault. Because the SKI does not contain similar bodies along the fault, it must postdate the event.

In conclusion, all the above observations suggest that the PRI was intruded before the SKI. During emplacement of the PRI, a rind of 'heterogeneous zone' crystallized at the margins of the magma chamber where the magma was contaminated by assimilated footwall rocks (Fig. 9B). In some areas the PRI and SKI are still separated by a ‘curtain’ of footwall rocks (29-60N-12W). However, in other areas only the rind of ‘heterogeneous zone’ is preserved at the contact between the PRI and SKI (Fig. 9C). Later emplacement of the SKI against igneous rocks of the PRI, explains why a rind of ‘heterogeneous zone’ is not present within the SKI and why hornfelsed inclusions are not as common in the SKI.
INTRODUCTION

An entirely different igneous package is present within the SKI relative to the PRI. The SKI consists of at least 17 igneous units (intersected in drill holes) that are correlatable along a 19 mile strike length that extends from the extreme eastern Babbitt Cu-Ni deposit through the Dunka Pit area and Maturi Cu-Ni deposit to the Spruce Road Cu-Ni deposit (Fig. 1). These 17 igneous units are referred to as the South Kawishiwi Troctolite Series (SKTS). The distribution and stacking arrangement of the SKTS units are schematically shown in Figure 10. Note that all SKTS units are not present throughout the SKI. This situation is exhibited by either the absence or addition of certain SKTS units within specific Cu-Ni deposit areas. Typically, only portions of the SKTS are present at any one locality; however, the stacking arrangement of the units is consistent, and some SKTS units exhibit overlaps into adjacent areas. In essence, many of the units of the SKTS are spatially restricted, and their overall distribution indicates that the SKI is ‘compartmentalized’ along its strike length.

In Figure 10, the SKTS units are referred to by acronyms in order to avoid confusing them with PRTS units, which use a Roman numeral system. The SKTS units are classed according to the dominant rock type, and/or rock packages, that can be correlated between drill holes. Because they are categorized in this manner, lateral thickness variations and pinch-outs are expected. Also, if a unit pinches out in one area and then a few miles away similar rocks reappear at the same stratigraphic horizon, the same unit designator is applied to both areas. Note that Figure 10 is broken into Cu-Ni deposit areas. Because changes in the stratigraphic pattern commonly occur down dip,
Figure 10. Generalized stratigraphy of the South Kawishiwi Troctolite Series.
some of the deposit areas are broken into two areas, e.g., Maturi versus Deep Maturi and Spruce Road versus Deep Spruce Road. In these instances the first deposit name refers to an area where numerous shallow drill holes were drilled, and the ‘Deep’ deposit name refers to an immediately adjacent area where scattered deep drill holes are present. The Highway 1 Corridor area refers to an area where six extremely deep drill holes occur on either side of Highway 1 (sections 2, 3, 10 & II, T.61N., R.11W., and section 34, T.62N., R.11W. - Plate I-A).

The units have been correlated in the ‘hung’ stratigraphic sections of Plates III, IV, V and XV-D. These sections were ‘hung’ on different units or collar elevations because the spatially-restricted nature of specific SKTS units was initially unknown and had to be determined as the investigation progressed. Cross-sections were constructed after the correlative igneous stratigraphy was determined for a particular area. Down dip changes in the SKTS are illustrated on the cross-sections. Both ‘hung’ sections and cross-sections are plotted at 1 inch = 200 feet. The locations of the sections are portrayed on Plate I (A and B).

Units of the SKTS, starting at the bottom, are described below. Again, it is important to note that not all SKTS units are equally present throughout the SKI. However, the stacking pattern is essentially consistent.

**BAN - Bottom Augite Troctolite/Norite**

The bottom-most unit of the SKTS is a heterogeneous mixture of augite troctolite and norite. Both are sulfide-bearing (trace to 5% by volume) and both may locally contain inclusions of BIF and GRAN. The BAN unit averages about 125 feet thick and varies from 10 to 380 feet thick. Norite is most common at the basal contact due to contamination of the magma from melting of the footwall rocks. It is not present in all drill holes, but when present the norite varies from 5 to 160 feet thick. Augite troctolite is the dominant rock type in the upper portion of the BAN Unit, but
also present are local gradations into olivine gabbro, gabbro, troctolite, and norite. These rocks are generally medium-grained, but fine- and coarse-grained zones are locally present.

Most of the basal massive sulfide occurrences are within the BAN Unit. These are generally pyrrhotite dominated (>90%). Maximum Cu values of up to 1.6% are associated with the basal massive sulfides (see SOKAWR.WK1 on computer disk in the back pocket of this report). Massive sulfides within the BAN Unit are intersected in the following Cu-Ni deposit areas: Serpentine prospect (see Zanko et al., in prep., for specific drill holes); Dunka Pit area (drill holes D-4, D-9, D-10, D-12, Du-11, E-5, E-6, E-7, E-9, B2-4, B2-9, B2-11, and B2-15); Birch Lake Cu-Ni-PGE-Cr deposit (Du-12); and the Spruce Road deposit (drill holes 11524, 32741, 32800, 34869, and AD-2). The spatial distribution of the basal massive sulfides intersected in these holes is illustrated by an ‘*’ placed adjacent to the collar of the drill hole on Plates II-B and XV-B. Interestingly, the basal massive sulfides in the Serpentine and Dunka Pit areas (Plate II-B) are generally found flanking areas where the BDD PO member of the Virginia Formation is present “up-dip” in the footwall rocks, or as inclusions positioned above the basal contact. This relationship suggests that the BDD PO member provided an excellent local sulfur source for the resultant nearby massive sulfides of the BAN Unit that settled to the basal contact. However, because the massive sulfides are not particularly copper-enriched, addition of sulfur to the magma from the BDD PO member may have only diluted the Cu and Ni values that were initially present in the magma.

Within the Dunka Pit area, massive oxide horizons (magnetite is dominant) are also locally present within the BAN Unit. The massive oxides are either closely associated with immediately adjacent BIF inclusions, or they are situated down-dip where BIF inclusions and/or BIF footwall are encountered (see Plates VI-B and IX-B). Because the massive oxides and BIF inclusions are present at relatively the same stratigraphic level within the SKTS, the massive oxides probably formed via melting of the BIF to produce an oxide-rich “restite.” Massive oxide horizons within the
BAN Unit are intersected within the following drill holes in the Dunka Pit area: D-4, D-5, D-6A, D-8, D-9, and E-5.

Thin section study of the BAN Unit (47 sections) reveals the following petrographic features. Olivine exhibits a wide variety of morphologies that range from round to amoeboid to poikilitic crystals. The first two types are the most common, but all types may occur in the same thin section. Both Cpx (5-35%) and Opx (0-10%) are typically present as interstitial to ophitic crystals. Increased amounts of Opx (up to 50%), and locally quartz (up to 10%), are associated with the noritic rocks near the basal contact. Minor amounts of intercumulus inverted pigeonite are locally found within all rock types of the BAN Unit. Plagioclase symplectite is only rarely present, but olivine symplectite is locally present (0-3%). Ilmenite is the dominant oxide phase, but rare composite ilmenite-magnetite grains are locally present.

The BAN Unit grades upward into dominantly troctolitic rocks of the BH Unit. Both the BAN and BH Units are similar in that they are heterogeneous and sulfide-bearing. In actuality, the BAN probably represents a contamination subzone of the BH along the basal contact.

**BH - Basal Heterogeneous Zone**

The main sulfide-bearing zone of the SKTS is referred to as the BH Unit. It is characterized by a mixture of troctolite with lesser amounts of anorthositic troctolite and augite troctolite. All rock types may alternate in an individual drill hole. Both homogeneous- and heterogeneous-textured varieties may also be present in all rock types; heterogeneous-textured rock is dominant. Contacts vary from gradational to sharp. Grain size is extremely variable and ranges from fine- to coarse-grained, with local pegmatitic zones. All rock types are generally sulfide-bearing and contain 0.5-5% disseminated sulfides by volume; locally present are zones with only rare to trace amounts. The BH Unit shows extreme thickness variations due to an overall thinning, both down
dip and along strike. In this regard, the BH Unit is the most variable of all the units of the SKTS. In general, wherever the U1 Unit (ultramafic one) is present in the SKTS, the BH Unit begins directly below it (Fig. 10). In the absence of U1, the BH Unit begins either directly below the U3 or PEG units (Fig. 10).

The average thickness of the BH Unit at Dunka Pit is about 385 feet, with a range of 130-650 feet. Sedimentary hornfels are commonly encountered within the BH Unit at Dunka Pit, though they are not particularly voluminous. The BH Unit also locally contains minor occurrences of: BIF; massive oxide; and semi-massive to massive sulfide. The latter occur in drill holes D-4, D-10, and D-13.

In the Dunka Pit to Birch Lake area, the BH exhibits a gradational down dip change into texturally homogeneous sulfide-barren rocks of the AT-T unit at the Birch Lake deposit. There, the BH Unit ‘merges’ into the U3 and BAN units (Fig. 10). To the immediate north of Birch Lake, the BH Unit is again distinguishable and varies from 90-160 feet thick. In the Maturi deposit area, the BH Unit averages about 130 feet thick and ranges from 60-250 feet thick. In the Spruce Road deposit area, the BH Unit exhibits a dramatic thickening and averages approximately 1,100-1,700 feet thick. Extremely heterogeneous zones, referred to as ‘Spruce Breccia’ by INCO geologists, are exceptionally common within the BH Unit and can possibly be correlated between drill holes (Plate XV-D). These zones are characterized by alternating fine- and coarse-grained troctolitic rocks that commonly exhibit abrupt contacts. The INCO geologists felt that the fine-grained zones represented inclusions of early chilled material and thus often referred to such zones as ‘Spruce Breccia.’ However, heterogeneous troctolite was also used by other INCO geologists for the same type of texture.

Examination of 50 thin sections from the BH Unit reveals the following unique petrographic features: 1) olivine occurs in a variety of morphologies - round to amoeboid morphologies are
dominant; 2) Opx is present up to 5% and occurs as rims around olivine that often grade outward into ophitic crystals; 3) up to 30% poikilitic inverted pigeonite is locally present; 4) plagioclase symplectite (wormy plagioclase and Opx on the edge of plagioclase crystals) is rare; and 5) ilmenite is the dominant oxide and only rare composite ilmenite-magnetite grains are locally present.

Overall, the BH Unit of the SKTS is similar to Unit I of the PRTS. Both units are the main sulfide-bearing zones, and both units occur near the base of the SKI and PRI, respectively. However, the similarities end there. Augite troctolite is the dominant rock type of Unit I, and troctolite is the dominant rock type of the BH Unit. Plagioclase symplectite is common within Unit I, but it is rare in the BH and BAN units of the SKTS. Inverted pigeonite is present (<2%) in most units of the SKTS, but it is rare in the PRTS units. Lastly, sedimentary hornfels inclusions are common to Unit I; whereas, olivine-rich ultramafic horizons are more common to the BH Unit.

At the beginning of this investigation, the Serpentine Cu-Ni deposit was presumed to be within the PRI. However, review of thin sections indicates that rocks in the Serpentine deposit do not contain plagioclase symplectite, and inverted pigeonite is commonly present in trace amounts. These observations suggest that the Serpentine area rocks are petrographically similar to SKTS units, and thus the Serpentine deposit is located within the SKI. The rock units present in the Serpentine area have been tentatively assigned SKTS unit designators on Plate VIII-B.

U3 - Ultramafic Three

At least three ultramafic-troctolite packages are present within the SKTS; the U3 Unit is the lowermost of these three packages. In the Dunka Pit and Birch Lake deposit, the U3 Unit directly overlies the BAN Unit, but in other areas the U3 and BAN units are separated by the BH Unit (Fig. 10). In some areas, the U3 Unit occurs near the bottom of sulfide-bearing units of the SKTS; however, the U3 Unit marks the top of the sulfide-bearing rocks in the Birch Lake and
Maturi deposit areas. The U3 Unit is characterized by a zone of alternating ultramafic (picrite-peridotite) and troctolitic horizons with lenses and pods of oxide-bearing (>5%) ultramafic and/or massive oxide. Up to 20 individual ultramafic horizons have been intersected in the U3 zone; whereas, in some areas the U3 is defined by only one ultramafic horizon. The ultramafic rocks are characterized by peridotite, picrite (melatroctolite), oxide picrite, and olivine-rich (>40%) troctolite; oxide picrite is generally the dominant rock type. Thicknesses of the ultramafic horizons vary from <1 foot to 16 feet. Contacts with alternating troctolitic horizons are sharp to gradational and are almost always subhorizontal. Unfortunately the contacts are rarely preserved in drill core because the U3 Unit is commonly split (1/4 core is also common). Massive oxide horizons are commonly found within the U3, and these range from 6 inches to 28 feet thick. Collectively, up to 47 feet of massive oxide may be found in a particular drill hole (up to five horizons were intersected in one drill hole). The intervening troctolitic rock horizons of U3 are characterized by: troctolite, augite troctolite, anorthositic troctolite, and pegmatitic troctolite. Heterogeneous troctolite is the dominant rock type of this group. Overall, the thickness of U3 averages about 100 feet and varies from 3 to 410 feet. Volumetrically, the ultramafic horizons account for about 33% (range of 5-100%) of the U3 Unit. Disseminated sulfide mineralization is always present within the rocks of U3 and varies from trace amounts up to about 5%. Chlorine-rich drops are commonly found coating the drill core of ultramafic and massive oxide horizons within the U3 Unit. Almost all significant PGE occurrences that have been found within the SKI are associated with the U3 Unit. High Cr values are also associated with the U3 Unit regardless of the PGE content. The spatial distribution of the U3 Unit within the SKI is portrayed in Figure 11.

The U3 Unit, and its related massive oxide horizons, occurs at the same stratigraphic level within the SKTS as the Biwabik Iron-formation. In some shallow holes drilled near the margin of the SKI, BIF inclusions are found within and/or immediately adjacent the U3 Unit. In the deeper
drill holes that were put down into the interior of the SKI, no BIF inclusions are directly associated with U3 Unit. However, in these instances BIF inclusions and/or BIF footwall are encountered updip at about the same stratigraphic level. All these correlations suggest that the massive oxide horizons of the U3 Unit are empirically related to intruded and assimilated BIF that formed an oxide-rich ‘restite’ within the intruding magma. The massive oxide horizons are characterized by magnetite with lesser amounts of plagioclase and olivine. Chromium-bearing spinels are
Figure 11. Distribution of the U3 Unit within the South Kawishiwi intrusion.
identified within the massive oxide (Sabelin and Iwasaki, 1985). Composite magnetite-ilmenite grains are locally present in minor amounts. Green pleonaste, or hercynite, is present as: 1) lamellae parallel to (100) and (111); 2) round blobs situated at the junction of three or more magnetite grains (these may be equal in size to the magnetite grains); or 3) partial rims around magnetite grains. The magnetite grains are typically round in shape (up to 3 mm), but gradations from sintered, or welded, magnetite grains to coalesced (annealed) groups of magnetite grains are common. Alapieti (1991) has referred to the coalesced grains as exhibiting atoll-like textures. He feels that they formed by sintering of oxide grains derived from the BIF in a manner described by Hulbert and Von Gruenewaldt (1985). The sintered atoll-like magnetite grains are commonly enclosed in coarse-grained, poikilitic plagioclase, and to a lesser extent, in poikilitic olivine. Alapieti (pers. comm.) refers to this texture in thin section as a ‘2 in 1 rock’ because it looks as if the texture is the result of two thin sections superimposed on each other. On Plate XII, the ‘2 in 1’ term is used wherever atoll-like magnetite ‘floating’ in plagioclase is recognized in drill core. In addition to these morphologies, round, subhedral olivine and intercumulus plagioclase are also present in the massive oxide horizons. The above petrographic descriptions are based on a study of 35 thin sections collected from massive oxides within the U3.

In thin section, the ultramafic horizons (29 thin sections) of U3 are characterized by round to polygonal olivine grains that tend to meet at triple point junctions. Weakly amoeboid olivine is locally present, and poikilitic olivine is present only rarely. Plagioclase is always intercumulus, but locally it is poikilitic and encloses olivine. Cpx is generally present in amounts <5% and occurs as intercumulus material that is locally ophitic. Opx occurs as partial rims around olivine when it is present in trace amounts. However, when Opx is present in amounts of up to 15%, it occurs as round (subhedral) to tabular grains (cumulus?). When the ultramafic layers contain more than 5% oxide, the dominant oxide is magnetite. On the other hand, when the oxide content is lower,
Ilmenite is dominant. The ilmenite commonly contains composite zones that are tentatively identified as titanium chromite. Similar looking grains have been previously identified, and analyzed, by Severson (1991) in the troctolitic rocks of the PRI. Microscopic magnetite stringers are commonly found within individual olivine grains - these are a product of serpentinization. Thin magnetite veins up to 0.5 mm across, also a product of serpentinization, are occasionally identified in drill core.

Review of 21 thin sections collected from the troctolitic horizons of U3 indicate that both magnetite-ilmenite and ilmenite-magnetite composite grains are present throughout the U3 Unit. Olivine is typically round to amoeboid, but poikilitic olivine is locally present. Cpx is typically intercumulus to ophitic, and Opx is present as partial rims around olivine. Inverted pigeonite is found in a few samples collected from the troctolitic horizons. Coarse green pleonaste is in one thin section of an oxide-bearing augite troctolite. Plagioclase symplectite is only rarely present in the troctolitic rocks of the U3 Unit.

Sulfides are commonly associated with all rock types of the U3 Unit. Typically present are: pyrrhotite, chalcopyrite, cubanite and pentlandite. In addition, secondary (or remobilized) sulfides are also found and include: bornite, chalcocite, mackinawite, and micro-cracks filled with chalcopyrite. These secondary sulfides suggest that some sulfide remobilization, and possibly PGE remobilization, occurred within the U3 Unit.
PEG - Pegmatitic Unit of Foose (1984)

The PEG Unit is a zone wherein pegmatoids (1-2 cm grain size) and gradational pegmatites (>2 cm grain size) are common. The main criteria used in the recognition of the PEG Unit is its presence directly above the U3 Unit. Only after the U3 is correlated between drill holes is it apparent that above it is a fairly consistent zone of scattered pegmatoidal and pegmatitic rocks. In the absence of the U3 Unit, the PEG is not readily distinguished. However, Foose (1984) recognized the PEG zone and utilized it as a main marker bed in a correlation of ten drill holes, even though he did not specifically correlate the U3 Unit. He referred to this zone as the Pegmatoidal unit (also called Unit II) and noted that, ‘The most clearly traceable layer is a 30 to 100 m thick plagioclase-rich and commonly pegmatoidal section at the base of the sulfide-free zone which is in sharp contact with the underlying sulfide-bearing zone. The pegmatoids ... are not always present...’ (Foose and Weiblen, 1986, p. 12) This same unit is distinguished in this investigation. Another criteria used in the recognition of the PEG is that it is the first zone that commonly contains sequences of heterogeneous rock, in contrast with the overlying SKTS sequences of texturally homogeneous rock. The PEG Unit is present in the Birch Lake, Maturi-Deep, Maturi, and Deep Spruce Road areas (Fig. 10). It is distinguished with some difficulty in the Highway 1 Corridor area. In most of these areas, the PEG Unit directly overlies sulfide-bearing rock of the U3, BH, and BAN units. Above the PEG, the rocks are barren of sulfides. Minor scattered sulfide occurrences are localized within the PEG Unit. Minor Cl-drop coated drill core is also scattered within the PEG Unit.

Rock types within the PEG Unit are often varied within a single drill hole. The dominant rock types are texturally heterogeneous troctolite and anorthositic troctolite; thick homogeneous zones are locally present. Augite troctolite, olivine gabbro, and troctolitic anorthosite are locally present. Grain size is usually medium- to very coarse-grained. These rocks grade into pegmatoidal
(1-2 cm) and pegmatitic (>2 cm) zones that vary from 1 to 97 feet and 1 to 51 feet thick, respectively. Most of these zones are plagioclase-rich and include: anorthositic troctolite, troctolitic anorthosite, anorthosite, anorthositic gabbro, and gabbroic anorthosite. The upper contact of the PEG is defined by the uppermost occurrence of either: 1) pegmatitic zone - below this the PEG Unit contains local pegmatitic zones; or 2) heterogeneous zone - below it the rock is commonly heterogeneous and contains local pegmatitic zones. In some instances, the entire PEG Unit consists of a thick pegmatoidal unit; in this instance the upper contact is usually sharp. The lower contact is usually sharp with the U3 Unit. Locally, pegmatitic zones are present in the upper portions of the U3. The overall thickness of the PEG Unit averages about 95 feet with a range of 10-260 feet. The spatial distribution of the PEG Unit is illustrated in Figure 12.

Thin section study of the PEG Unit (22 sections) reveals the following features. Olivine generally occurs as amoeboid grains, but round-equigranular and poikilitic olivine are also present. Cpx occurs as interstitial to ophitic grains; Opx is present as partial rims around olivine. Plagioclase symplectite is common to the PEG Unit and ranges from trace amounts to 7%. All rock units above the PEG Unit contain plagioclase symplectite; whereas, it is relatively rare in all the underlying rock units below the PEG. Ilmenite, with composite titanium chromite (tentative identification), is the dominant oxide phase. Only rare ilmenite with composite magnetite are found within the PEG Unit.
Figure 12. Distribution of the PEG Unit within the South Kawishiwi intrusion.
AT-T - Anorthositic Troctolite to Troctolite

Wherever a texturally homogeneous, sulfide-barren zone of troctolitic rock is encountered above the PEG Unit, it is referred to as the AT-T Unit. Anorthositic troctolite grading into troctolite, commonly present in alternating zones, characterizes the AT-T Unit. Anorthositic troctolite is dominant in some holes, and troctolite may be dominant in other holes. The AT-T Unit is situated between the MAIN AGT and PEG units in the Birch Lake and Maturi deposit areas (Fig. 10). In the area from Dunka Pit to Birch Lake (1-2 miles down dip), the BH Unit grades laterally into texturally homogeneous and sulfide-barren rocks of the AT-T Unit. This suggests that the BH and AT-T units may be synchronous; the main distinction between the two are variations in homogeneity and sulfide content. The AT-T Unit averages about 380 feet thick and ranges from 70-1,200 feet thick. There are no unique petrographic features associated with the AT-T Unit, except that plagioclase symplectite is common, and ilmenite, with minor composite magnetite, is dominant in the 20 thin sections studied.

U2 - Ultramafic Two

The U2 Unit is the middle ultramafic-troctolite package of the SKTS. At Dunka Pit, it is situated about in the middle of the sulfide-bearing rocks of the BH Unit. North of Dunka Pit, the U2 Unit is only locally present, and it is difficult to correlate in drill holes in an area extending from the Birch Lake deposit to the Maturi deposit. At the Spruce Road deposit, a middle ultramafic-troctolite package is once again encountered in the middle of the BH Unit. Therefore, wherever three ultramafic-troctolite packages are encountered, the middle package is referred to as the U2 Unit (Fig. 10). The U2 Unit is similar to the U3 Unit, except that massive oxide horizons and oxide-rich ultramafic layers are conspicuously absent in U2, with the exception of drill hole, BI-68 (Plate III). In this drill hole massive oxides and ultramafic horizons appear to be correlative with
a middle ultramafic package, but correlation with the U3 Unit is also a possibility. Overall, the U2 Unit averages about 90 feet thick with a range of 5-425 feet thick. As many as 23 individual ultramafic horizons are encountered within the U2 Unit. The ultramafic horizons (picrite-peridotite) vary from 1 to 40 feet thick and volumetrically account for about 36% (range of 5-100%) of the U2 Unit. Contacts with the alternating troctolitic horizons range from gradational to sharp. The contacts are generally subhorizontal, but steeply-inclined and irregular contacts (slumped?) are locally present. For the most part, the drill core of the U2 Unit is split, and contact relationships are not preserved. Both troctolite and anorthositic troctolite are present between the ultramafic horizons. Sulfides are only present within the U2 Unit when it is within the BH Unit. Chlorine-rich drops commonly coat the drill core of the ultramafic horizons within the U2 Unit. Serpentinitization of the ultramafic horizons varies from fresh rock to highly serpentinitized rock. Petrographically, the U2 Unit is similar to the U3 Unit, but only rare composite ilmenite-magnetite composite grains are present in U2. Ilmenite commonly contains composite patches of titanium chromite (tentative identification). In some thin sections, a primary igneous foliation is defined by aligned plagioclase laths. Nineteen thin section samples are available from the ultramafic horizons of the U2 Unit.

**U1 - Ultramafic One**

The uppermost package of alternating ultramafic and troctolitic horizons defines the U1 Unit of the SKTS. It is similar to the U2 Unit, except that it occurs higher in the stratigraphic section, and the rock units above it are generally sulfide-barren. In the Dunka Pit area, the U1 Unit generally marks the top of the sulfide-bearing rocks. The U1 Unit is only locally present in an area extending from the Birch Lake deposit to the Maturi deposit. There, the U1 is void of sulfides and the rocks immediately below it are also sulfide-barren. At the Spruce Road deposit, the U1 Unit is
again consistently present in most drill holes and it is sulfide-bearing. Correlations using INCO drill logs suggest that the U1 occurs near the top of a thickened sulfide-rich BH Unit (Fig. 10). Overall, the U1 Unit is consistently present in the southwest and northeast portions of the SKI. Its spatial distribution is illustrated in Figure 13. Because both the U1 and U2 units occur in the same areas, their collective spatial distribution is portrayed in Figure 13. In the Birch Lake deposit area, the U1 Unit is 'replaced' down dip by a thin zone of uncorrelative heterogeneous rock types and textures (Plate XI). In the Dunka Pit deposit, both the U1 and U2 units 'disappear' up dip as the steeply-rising basal contact is approached (Plates VI-A, IX and X).

Volumetrically the internal ultramafic horizons of U1 account for about 55% (range of 10-100%). Picrite is the dominant ultramafic rock type, but peridotite, dunite, and zones of olivine-rich troctolite are also present throughout U1. As many as eleven ultramafic horizons, ranging in thickness from 1-52 feet, may be encountered in a single drill hole that intersects the U1 Unit. In some areas, the U1 Unit is defined by only one ultramafic horizon. The ultramafic horizons generally exhibit gradational upper contacts and sharp subhorizontal lower contacts (with increasing olivine content with depth), suggesting that crystal settling may have been important in their formation. Locally, both gradational upper and bottom contacts are present in the individual ultramafic horizons. Additional contact features include steeply-inclined sharp contacts (ultramafic dikes), and highly irregular, steeply-inclined, sharp bottom contacts. These suggest, respectively, that
Figure 13. Distribution of the U1 and U2 units within the South Kawishiwi intrusion.
filter-pressing and slumping mechanisms are locally important. Cl-drop coated core is commonly found associated with the ultramafic horizons of the U1 Unit. No massive oxide or oxide-rich ultramafic layers are associated with the U1 Unit.

The intervening troctolitic horizons of U1 consist of anorthositic troctolite and troctolite; both are present in near equal amounts. These rock types are typically texturally homogeneous, but present locally are texturally heterogeneous rocks. All rock types of the U1 Unit are sulfide-bearing, but generally a higher percentage of sulfide occurs in the troctolitic units. Petrographically, the U1 and U2 units are very similar. Ilmenite is the dominant oxide, and it locally contains composite titanium chromite blebs (tentative identification). Composite ilmenite>magnetite grains occur in rare amounts in the rocks of the U1 Unit. Plagioclase symplectite is also rare.

**MAIN AGT - Main Augite Troctolite**

The MAIN AGT is characterized by a zone where augite troctolite is the dominant rock type. It is present nearly everywhere within the SKI (Fig. 10) in an area extending immediately northeast of the Babbitt deposit through the Dunka Pit, Birch Lake, and Maturi areas. It is conspicuously absent in Spruce Road and the Highway I Corridor area (Fig. 10). The overall spatial distribution of the MAIN AGT is shown in Figure 14. The MAIN AGT averages about 900 feet thick but varies from 270 to 1,380 feet thick. The extreme range in thickness is because the MAIN AGT consistently thins down dip. In many instances, the MAIN AGT loses its identity down dip due to lateral gradational changes into augite-poor troctolitic rocks. Both the lower and upper boundaries are gradational into other units of the SKTS. In one drill hole (K-4), abundant anorthosite inclusions are present in the bottom 5 feet of the MAIN AGT.
Figure 14. Distribution of the MAIN AGT Unit within the South Kawishiwi intrusion.
In the Dunka Pit area, the MAIN AGT is encountered only in the deepest drill holes shown in Figure 15-A. In these holes, a thick section of MAIN AGT is intersected in the top 800-1,400 feet. However, within a very short distance to the west of these holes, (within 600-1,200 feet) the MAIN AGT is entirely absent, and the UW Unit (Updip Wedge) is present at about the same stratigraphic level. This situation indicates that the contact between the MAIN AGT and UW units is very steeply inclined. The nature of the contact between the two is portrayed in Figure 15-B and in several cross-sections included in this report. Note that on the 'hung' section of Plate III, the contact between the MAIN AGT and UW units is expressed as being highly undulatory. This is only the result of projecting drill holes across the steeply-inclined contact.
Figure 15. Stratigraphic relationship of the MAIN AGT Unit to the UW Unit in the Dunka Pit area.
As the name implies, the dominant rock type of the MAIN AGT is augite troctolite. It is commonly texturally homogeneous, medium-grained (locally medium- to coarse-grained), and contains variable amounts of coarse to very coarse-grained intercumulus to ophitic Cpx and coarse-grained oxides (composite ilmenite-magnetite). Due to variations in Cpx and plagioclase content, the augite troctolite commonly grades into plag-rich augite troctolite, anorthositic troctolite, troctolite, and olivine gabbro. Also present within the MAIN AGT are localized gradational zones of anorthositic gabbro, gabbroic anorthosite, and troctolitic anorthosite. Gradational zones of pegmatitic augite troctolite to gabbroic zones are sporadically present, but these are not common. A subhorizontal primary igneous foliation, defined by aligned plagioclase laths, is locally present in all rock types but cannot be correlated between drill holes.

In many of the drill holes put down in the Dunka Pit area, the MAIN AGT is intruded by late lenses of OUI and granitic rocks. These late hybrid rocks are unique in that they occur at about the same stratigraphic level near the base of the MAIN AGT. It is unknown if these hybrid rocks are distributed within a subhorizontal zone, or the hybrid rocks are subvertical lenses that were coincidentally intersected repeatedly at the same general stratigraphic horizon. Dips of the contacts of these hybrid rocks with the MAIN AGT are varied and cannot be used to resolve these questions. These hybrid rocks are present in the following holes on Plate III: D-1, D-3, D-6A, D-9, E-5, and E-7.

Thin section study of the MAIN AGT (109 sections) reveals several petrographic features that are unique to the unit. Olivine occurs in at least four different morphologies, but round-equant and amoeboid varieties are dominant. Inverted pigeonite is very common. It is present in over half of the sections in amounts up to 9%. Opx is extremely common (up to 8%). It occurs as thick rims around olivine that grade outward into interstitial and locally subophitic Opx crystals. Epitaxial biotite and plagioclase symplectite (up to 5%) are extremely common in the MAIN AGT. Olivine symplectite is fairly common (up to 3%). Finally, though ilmenite is dominant, composite magnetite
is commonly found associated with it in almost all thin sections. What is unique about these features is that they are not found in the units below the MAIN AGT Unit.

LOW AGT - Lower Augite Troctolite

A second zone where augite troctolite is the dominant rock type is called the LOW AGT. It is present below the MAIN AGT in an extremely localized area that extends from immediately north of the Birch Lake deposit north to, and including, the Maturi deposit. Both the MAIN AGT and LOW AGT are very similar, but about 100-900 feet of the AT-T Unit separates the two. The LOW AGT is present in only six drill holes that include: Du-6, Du-13, Du-14, Du-16, K-8, and KA-3. In these holes, the unit ranges from 40 to 500 feet thick. It is petrographically similar to the MAIN AGT in all respects.

UW - Updip Wedge

The UW Unit is present only in the Dunka Pit area (Fig. 16). The rocks of this unit are entirely different from rocks of the MAIN AGT that occur at the same stratigraphic level in the SKTS. Because these rocks occur updip of the MAIN AGT, and because they are positioned in a wedge-shaped zone located between the MAIN AGT and a steeply-rising basal contact (Fig. 10), they are referred to as the Updip Wedge. The UW Unit is characterized by sulfide-bearing troctolite, anorthositic troctolite, and augite troctolite. Troctolite is the dominant rock type. All rock types alternate within the UW, and all rock
Figure 16. Distribution of the UW Unit within the South Kawishiwi intrusion.
types may be homogeneous- or heterogeneous-textured. The entire unit is heterogeneous overall as rock types and textural varieties cannot be correlated between drill holes. Sulfide content varies from rare amounts to 3%. Sedimentary hornfels inclusions (Virginia Formation) are common within the UW Unit.

The UW Unit varies from 100 to 950 feet thick within a very limited area because of its wedge-shaped character. It is very similar in appearance and rock type to the underlying BH Unit. The two are only distinguished when they are separated by the U1 Unit. However, when the U1 Unit ‘disappears’ updip, these two similar-looking units are no longer divided by a ‘correlation barrier,’ and actual unit designation is tenuous at best. Toward the interior of the Complex, the UW Unit abuts against, and wedges out against, the steeply-inclined contact of the MAIN AGT. As can be seen in Figure 15-B, a small wedge of UW Unit locally occurs between the MAIN AGT and U1 units.

Near the top and middle of the UW Unit are two ultramafic horizons that are referred to as the UW-1 and UW-2 subunits, respectively. The ultramafic subunits are only encountered in drill holes that intersect a thick section of the UW Unit. These drill holes are widely spaced and include BI-432, D-10, and D-8 (Plate III). Because the ultramafic subunits are present in so few drill holes, and so widely-spaced, it is difficult to determine if they can actually be correlated. Cl-drop coated drill core is associated with the UW-2 subunit in drill hole BI-432.

The UW Unit is petrographically similar to the BH Unit, except that the UW Unit (53 thin sections) contains: 1) common plagioclase symplectite; 2) thicker Opx rims around olivine (locally Opx is intercumulus to subophitic and present up to 17%); 3) common olivine symplectite; and 4) ilmenite is dominant (with composite magnetite). The UW Unit is petrographically similar to the MAIN AGT (but the two contrast in all other megascopic aspects).
AT&T - Anorthositic Troctolite and Troctolite

The AT&T Unit is a thick, monotonous zone of alternating anorthositic troctolite and plagioclase-rich (65-70%) troctolite, with minor zones of troctolitic anorthosite and augite troctolite. Changes between the various rock types are generally gradational, but abrupt contacts are also common. In most of the drill holes, troctolite is the dominant rock type (with local gradations to augite troctolite). Anorthositic troctolite accounts for about 2-40% of the AT&T Unit. All rock types are generally medium-grained and homogeneous-textured, but local heterogeneous zones, up to 400 feet thick, are scattered throughout the AT&T.

Because the AT&T Unit is one of the highest units of the SKTS, it is intersected in the top portions of very deep drill holes put down toward the interior of the Complex. Out of 22 drill holes that encounter the AT&T, only 11 holes intersect a complete, or nearly complete, vertical section of the AT&T. In these holes, the AT&T varies from 1,200 to 2,000 feet thick. The top of the unit is defined by a fairly consistent ultramafic horizon, called High Picrite #1, which is present in eight drill holes. Toward the bottom of the unit, troctolitic rocks grade with depth into the augite troctolite of the MAIN AGT. Where the MAIN AGT is not present (as at Spruce Road), the AT&T Unit exhibits an abrupt to sharp contact with heterogeneous-textured, sulfide-bearing rocks of the BH Unit.

Within the Birch Lake deposit area, another fairly consistent ultramafic horizon, called High Picrite #2, occurs near the top of the AT&T Unit. It is situated about 300-500 feet below the High Picrite #1 subunit. Both High Picrite #1 and #2 are characterized by olivine-rich troctolite and picrite. Both also generally exhibit gradational top contacts and abrupt to sharp subhorizontal bottom contacts. The upper ultramafic horizon (#1) is 2-8 feet thick (6 foot thick average), and the lower horizon (#2) is 1-13 feet thick. These two ultramafic horizons are correlated on Plates IV, XI, and XIII. Cl-drop coated drill core is locally associated with both horizons.
Examination of 27 thin sections collected from the AT&T Unit reveals the following distinguishing petrographic features. Opx is present up to 4%; it occurs as thick rims around olivine and as intercumulus material. Inverted pigeonite is present as trace amounts in ten of the sections. Plagioclase symplectite (up to 2%) and olivine symplectite are present in ten of the sections. Ilmenite and magnetite are present in near equal amounts and both occur together in composite grains. Alapieti (1991) found baddeleyite in one thin section (Du-15, 461.7 ft).

**AT(T) - Anorthositic Troctolite (locally Troctolite)**

In the uppermost 150-1,200 feet of ten drill holes is a unit referred to as AT(T) Unit. Less than 600 feet are intersected in all but two holes. The top of the unit is not defined, and the bottom of the unit is marked by the High Picrite #1 subunit. The AT(T) is a monotonous zone of anorthositic troctolite and troctolitic anorthosite that locally grades into troctolite and rare augite troctolite zones. All rock types are homogeneous-textured and medium- to coarse-grained. This unit is petrographically similar to the underlying AT&T Unit (11 thin sections).

**HIGHWAY 1 CORRIDOR AREA ROCKS**

An entirely different package of rocks is present within the Highway 1 Corridor Area (Fig. 10). The igneous strata in this area are defined by six extremely deep drill holes (each 4,000-5,200 feet deep) that were drilled in an area that straddles Highway 1. The drill holes that define the Highway 1 Corridor (HIC) include: Du-3, Du-4, Du-8, NM-3, NM-4, and NM-5 (also referred to as NE-5). Locations of the holes are plotted on Plate I-A.

The rock units that are present in the extreme top and bottom portions of the six drill holes appear to be SKTS-type units, and thus, SKTS unit designators are used for them on Plate IV. However, an entirely different, or exotic, package of rock is present in the middle portions of the
drill holes, and new unit designators are used on Plate IV. Because anorthosite is the dominant rock type in the middle portions of the holes, the H1C may be related to the Anorthositic Series rocks that have been mapped (Green et al., 1966) as cropping out about 3-4 miles away to the southeast. Also, because the H1C occurs as an ‘island‘ within the SKTS, it may represent a rather large inclusion of the Anorthositic Series. This would imply that the Anorthositic Series is much older than the SK1, which is in contrast to the ages obtained by Paces and Miller (1993). However, no age dates are available in the immediate area of this investigation, and much more detailed age dating of the various subintrusions of the Complex is warranted. If the central portion of H1C is an inclusion, the size is formidable (the exotic rocks are present in about 3,500 feet of vertical thickness).

All rock types present within the H1C are exhibited on Figure 10 and Plate IV. They are described below, from top to bottom.

**AT(T) - Anorthositic Troctolite (locally Troctolite)**

A monotonous sea of homogeneous-textured anorthositic troctolite, locally grading to troctolite and augite troctolite, is intersected in the top 60-970 feet of the holes drilled into the H1C. These rocks are very similar to and correlate with the AT(T) Unit of the SKTS. This unit is described above (p. 93).

**T-AGT - Troctolite to Augite Troctolite**

The T-AGT Unit is characterized by alternating troctolite and augite troctolite in the uppermost 70-450 feet of the H1C. These rocks are medium-grained and texturally homogeneous, but heterogeneous zones are locally present. This unit is much higher above the basal contact than the MAIN AGT, and the two units are not correlatable. Both the upper and lower contacts of the
T-AGT are gradational into the AT(T) and UPPER PEG units, respectively. No thin sections are available from the T-AGT Unit.

**UPPER PEG - Upper Pegmatitic Zone**

The UPPER PEG Unit (77-139 feet thick) is intersected in three drill holes (Plate IV). It is characterized by thick intervals of pegmatoidal troctolite that alternate with coarse- to very coarse-grained, heterogeneous-textured troctolite and anorthositic troctolite that commonly contain thin pegmatitic intervals. No thin sections of the UPPER PEG Unit are available for study.

**"INCL" - Inclined Inclusion of Basalt**

A moderately to strongly magnetic, fine-grained rock of gabbroic composition is intersected in five drill holes of the HIC. Because the ‘INCL’ is so fine-grained, it was originally logged by the author as several different field terms. However, all of these field terms are exceptionally correlative in drill holes, and the term ‘INCL’ is utilized to encompass them all. The ‘INCL’ appears to be an shallow-dipping inclusion of hanging wall material. It is almost always characterized by a fine-grained rock that exhibits a granoblastic texture. Generally, the rock is massive, but it often grades into local zones that contain vesicles. The vesicles are defined by either plagioclase-filled 'spots' or round ovoids filled with plagioclase and/or Opx ± Cpx. Also, Opx-filled veins and bifurcating lenses, or 'sweat-outs', are locally present. The ‘INCL’ consistently contains 5-15% fine-grained, disseminated, equant to elongated magnetite grains. Minor zones with massive magnetite (up to 6 inches) and magnetite-rich wisps/beds are scattered in some of the drill holes. The ‘INCL’ is, therefore, inferred to be a basaltic inclusion that is very similar to portions of the Colvin Creek Hornfels. In some drill holes, the ‘INCL’ is intruded by fine-grained noritic rocks that exhibit
gradational contacts. In drill hole Du-8, noritic rocks at 715-717 feet contain round anorthosite inclusions up to 4 cm across.

Drill hole intersections of the ‘INCL’ are associated with the following holes: NM-3 (292-717 ft.), NM-4 (1086-1663 ft.), NM-5 (1541-1842 ft.), Du-3 (453-488 ft.), and Du-8 (602-944 ft.). Five variations of three point problems were conducted using the elevation of the base of the ‘INCL’ in these drill holes. All variations indicate that the inclusion uniformly dips at about 11°-15° to the SE to S8°E. The ‘INCL’ crops out in at least two separate areas (see Plate I-A). Bonnichsen (1972) describes outcrops in the SE 1/4 of section 34 (T.62N., R.11W.) that are very similar to rocks intersected in nearby drill hole NM-4. These outcrops were mapped by exploration companies and were shown on corporate geologic maps that are on file at the MDNR. The second area of outcrop (section 4, T.61N., R.11W.) is taken from the Gabbro Lake geologic map of Green et al. (1966). In total, the ‘INCL’ is present in outcrops and drill holes within a three square mile area. Overall, the area of the ‘INCL’ is marked by an anomalous 300-400 nT magnetic high on the aeromagnetic map of the Gabbro Lake SW (or Bogberry Lake) Quadrangle (MGS open-file map).

In thin section (20 samples), the ‘INCL’ consists dominantly of: 40-60% granular/polygonal plagioclase; 15-35% granular to tabular Cpx; 5-20% granular to ophitic Opx; and 5-15% magnetite, with minor very fine-grained lamellae of ilmenite and ulvospinel (tentative identification) parallel to (111) and (100). Amoeboidal to poikilitic olivine is present in six of the thin sections studied. Inverted pigeonite is also present in five thin sections where it occurs as interstitial to poikilitic crystals.

No samples were collected from the ‘INCL’ for geochemistry in this investigation. Two samples were previously collected by the MDNR (data in SOKAWR.WK1 file - computer disk in back pocket). Bonnichsen (1972) collected a sample of the ‘INCL’ for geochemical analysis (no.4,
Table V-30) from drill hole NM-4. He stated that the rock had very low SiO₂ and high CaO contents ‘... which are anomalous for a volcanic rock.’ (Bonnichsen, 1972, p. 386)

In summary, the ‘INCL’ is a basaltic rock of the Colvin Creek (CC) variety. Because of its high magnetite content, it is different than the ‘typical’ basalt inclusions that have been correlated with the North Shore Volcanic Group. The ‘INCL’ is present as a shallow-dipping (11°-15°) sheet that is 300-500 feet thick and covers an area of about three square miles.

Beneath the ‘INCL’ and above the UPPER GABBRO Unit is an unnamed unit that is intersected in all six drill holes (Plate IV). The rocks of this 20-144 foot thick unit consist of a gradational mixture of troctolite, augite troctolite, and anorthositic troctolite, with minor amounts of anorthosite, troctolitic anorthosite, and gabbroic anorthosite. Both homogeneous-textured and heterogeneous-textured rocks are present in a particular drill hole. Specific rock types and textures do not correlate between drill holes. This unnamed unit exhibits a gradational bottom contact with the UPPER GABBRO Unit.

UPPER GABBRO

Oxide-bearing (5%) gabbro and olivine gabbro, with local augite troctolite and troctolite, typify the UPPER GABBRO Unit of the H1C. The rock is generally medium- to coarse-grained and heterogeneous-textured, but homogeneous-textured zones are also present locally. Olivine content is the most variable, and gradations from augite troctolite to gabbro are present throughout this unit. Note that the field term of augite troctolite (agt) is most often listed for the drill holes that intersected the UPPER GABBRO Unit on Plate IV. However, thin section study of this unit (15 samples) indicates that the dominant rock type is olivine gabbro and gabbro. The UPPER GABBRO ranges from 20 to 855 feet thick. It overlies the AN-G GROUP unit, where both anorthositic and gabbroic rocks are intermixed. The UPPER GABBRO Unit is very similar to the gabbroic rocks of
the AN-G GROUP, but is given a specific unit name in this study because a thick sequence was intersected and could be correlated in several drill holes.

Unique petrographic features associated with the UPPER GABBRO Unit include: olivine is present as only amoeboid to weakly poikilitic crystals; plagioclase symplectite and olivine symplectite are present locally; and coarse-grained apatite is locally present in trace amounts to 5%. Ilmenite is the dominant oxide, but it commonly contains composite magnetite.

AN-G GROUP - Anorthosite-Gabbro Group

An extremely thick sequence of intermixed anorthositic and gabbroic rocks are intersected in the bottom portions of drill holes put down in the HIC. Anorthositic rocks (anorthosite, troctolitic anorthosite, and minor anorthositic troctolite) comprise about 40-70% of the AN-G GROUP. Troctolitic rocks (troctolite grading to anorthositic troctolite) and gabbroic rocks (gabbro, olivine gabbro, and augite troctolite) generally account for about 8-13% (45% in one hole) and 13-24% (56% in one hole) of the AN-G GROUP, respectively. Contacts between the anorthositic and gabbroic/troctolitic rock types are generally abrupt to sharp and subhorizontal, but gradational contacts are present locally. Because these two rock types cannot be correlated in drill holes, they are collectively lumped into the AN-G GROUP unit. This unit averages about 1,850 feet thick, with a range of 1,590-2,450 feet thick. Drill hole NM-5 intersects the AN-G GROUP in a 'piece-meal' fashion (on the edge of the HIC inclusion?) and is not included in the above listed averages. The known spatial distribution of the AN-G GROUP is illustrated in Figure 17.

The anorthositic rocks are generally homogeneous-textured, coarse- to very coarse-grained plagioclase-rich (>80%) rocks. They commonly exhibit primary igneous foliation, defined by aligned plagioclase laths, that vary from 20E-80E to the core axis (50E-70E is dominant). The amount of primary igneous foliation varies drastically from drill hole to drill hole and cannot be correlated
between drill holes. Variably saussuritized plagioclase is generally confined to the anorthositic zones. Uralitized zones are also scattered throughout some drill holes. The anorthositic rocks locally contain sulfide mineralization (<0.5%) that is scattered within the bottom few hundred feet of the AN-G GROUP in three drill holes (NM-4, Du-3, Du-8). In thin section (22 sections), the anorthosites consist of lath-shaped plagioclase with variable quantities of olivine (all morphologies),
Figure 17. Location of the Highway 1 Corridor (H1C) area.
Cpx (intercumulus to ophitic), and minor amounts of plagioclase symplectite and olivine symplectite. Ilmenite is dominant and only rarely contains composite magnetite. Several thin sections contain quartz, calcite, and/or amphibole (trace to 3%).

The gabbroic rocks, and gradational troctolitic rock zones, are generally heterogeneous-textured, oxide-bearing (3-7%), and medium-grained. Uralitized zones are scattered throughout some drill holes. Unique petrographic features (11 thin sections) of the gabbroic rocks of the AN-G GROUP include: olivine occurs in a variety of morphologies; Cpx is intercumulus to ophitic; plagioclase symplectite is extremely common (up to 10%); and ilmenite>magnetite composite grains are dominant.

Within the AN-G GROUP, semi-massive graphite zones are intersected in four drill holes that include: NM-3 (2414-2416 ft.), NM-4 (2663-2675 ft.), Du-3 (2352-2355 ft.), and Du-8 (3122-3126 ft.). Contacts with the enclosing anorthositic and gabbroic rocks are not preserved as the core has been split in all instances. The graphite distribution, shown on Plate IV, indicates that they are not horizontally correlative. Thus, the graphite-rich zones are probably present as near-vertical veins. This observation is substantiated by drill hole NM-4 in which a graphite zone was intersected in the original hole but was not intersected in a 1,000 foot thick redrilled portion of the hole. The graphite-rich zones contain variable amounts of plagioclase, pyrrhotite, quartz, Opx, and biotite. Chemical analysis of one graphite-rich zone, collected by the MDNR from drill hole NM-3, is included in SOKAWR.WK1 in the back pocket of this report.

PEG - Pegmatitic Unit of Foose (1984)

The PEG Unit of the SKTS is described previously. In the HIC area, it is difficult to distinguish the plagioclase-rich PEG Unit from overlying very coarse-grained anorthositic rocks of the AN-G GROUP. Generally, the PEG Unit is recognized by: a heterogeneous-texture, the
presence of scattered pegmatitic and pegmatoidal zones, and the presence of sulfides near the base of the PEG or in the underlying BH Unit.

**BH - Basal Heterogeneous Unit**

The BH Unit is described in a preceding section. It is the major sulfide-bearing unit of the SKI. It is also the major sulfide-bearing zone in the HIC where it ranges from 0 to 260 feet thick. The BH Unit contains several small BIF inclusions within NM-5 and GRAN inclusions within Du-8. Several ultramafic horizons (picrite-peridotite), presumably correlative with the U3 Unit, occur in NM-5.

**BAN - Basal Augite Troctolite-Norite**

The BAN Unit of the SKTS (described previously) is intersected in the bottom portions of all holes drilled into the HIC. The dominant rock type is norite, but augite troctolite is locally present in the top portions of the BAN Unit. Chilled norite zones and inclusions are locally present within medium-grained norites within drill hole NM-5. The BAN Unit varies from 10 to 300 feet thick beneath the HIC.

**DISCUSSION**

Most of the units described above are not equally present throughout all of the SKI. Because the specific units occur sporadically throughout the SKTS, determination of the age of one unit relative to another is severely hampered. This is also complicated by the overall stratigraphic pattern, which indicates that the SKI is not only ‘layered’ vertically, but is also compartmentalized horizontally along its strike length. In other words, the SKI is itself a multiple intrusion in which
each of the individual units exhibit a finite spatial extent. The SKTS units overlap each other in a myriad of patterns, producing the stratigraphic pattern that is illustrated in Figure 10.

Bonnichsen (1972) previously correlated at least three igneous units within four drill holes in the Dunka Pit area. His uppermost unit corresponds to the MAIN AGT Unit of this investigation. The middle unit corresponds to the BH, U1, U2, and U3 units of this investigation. Bonnichsen’s lowest unit corresponds to the BAN Unit. Foose (1984) also correlated several igneous units within nine different drill holes. These igneous units were referred to as (from bottom to top) units I through VI (Foose and Weiblen, 1986). The PEG Unit of this investigation corresponds to Foose and Weiblen’s (1986) Unit II (also called the pegmatoidal layer by Foose, 1984), except for a discrepancy in drill hole Du-14 (I have picked a lower pegmatoidal layer as being correlative with the PEG based on how the U2 and U3 unit correlate in drill hole). Foose and Weiblen’s (1986) Unit V roughly corresponds to the MAIN AGT of this investigation. Not all of the units defined in this investigation are equally present in both Bonnichsen’s and Foose’s areas. This observation has lead to some difficulty in comparing the stratigraphies of these previous studies.
GEOCHEMISTRY

INTRODUCTION

Drill core samples were collected from most of the major lithologic units of the SKTS for whole rock, trace element, rare-earth element (REE), base metal, and precious metal analyses. A total of 80 drill core samples were analyzed (Table 1) and include: 55 SKTS samples; 3 PRTS samples (the BU Unit); 5 basalt inclusion samples; 4 BIF samples; 3 BIF Sill samples; 6 Giants Range (GRAN) samples; and 4 late granitic vein (gr) samples. Results are listed in the SOKSORT.WK1 data file in the back pocket of this report (paper copies will be provided upon request). In addition, PGE scans (Pt, Pd, Ir, Ru, Rh, Re, and Au) were conducted on all the samples (results included in the SOKSORT.WK1 data file).

Also, the geochemical results of previously sampled drill core intervals (prior to July 1992) were compiled into the following data bases (back pocket of this report): 1) SOKAWR.WK1 = includes whole rock, REE, etc., data; and 2) SOKAPM.WK1 = contains mainly precious metal analyses. These data were assembled from: Dahlberg, 1987; Dahlberg et al., 1989; Sabelin and Iwasaki, 1985, 1986; and private exploration company files that have been open filed at the MDNR. Whenever possible, these previously analyzed geochemical samples were assigned to corresponding SKTS igneous units.

The DNRSORT.WK1 file (abbreviated version of SOKAWR.WK1 data file) was compiled by removing all ‘improper’ samples from the SOKAWR.WK1 file. ‘Improper’ samples included: 1) samples that were collected across contacts - as a result contrasting rock types were geochemically mixed; 2) samples with poor whole rock totals (<98%); and 3) samples of massive sulfide zones. The DNRSORT.WK1 data file was used to construct some of the X-Y plots of this report.
### Table 1. Grouping of geochemical samples.

<table>
<thead>
<tr>
<th>Rock Unit</th>
<th>No. of Samples</th>
<th>Rock Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT(T)</td>
<td>2</td>
<td>An Troct</td>
</tr>
<tr>
<td>AT&amp;TT</td>
<td>2</td>
<td>An Troct &amp; Troct</td>
</tr>
<tr>
<td>MAIN AGT</td>
<td>6</td>
<td>Augite Troctolite (includes one duplicate sample)</td>
</tr>
<tr>
<td>U1</td>
<td>6</td>
<td>3 ultramafic &amp; 3 troctolitic samples</td>
</tr>
<tr>
<td>U2</td>
<td>5</td>
<td>ultramafics</td>
</tr>
<tr>
<td>U3</td>
<td>11</td>
<td>6 ultramafics, 2 troctolites, 3 massive oxides</td>
</tr>
<tr>
<td>PEG</td>
<td>5</td>
<td>heterogeneous troctolite and pegmatitic zones</td>
</tr>
<tr>
<td>BH</td>
<td>3</td>
<td>heterogeneous, sulfide-bearing troctolites</td>
</tr>
<tr>
<td>BAN</td>
<td>7</td>
<td>3 Augite troctolites &amp; 4 norites</td>
</tr>
<tr>
<td>BU</td>
<td>3</td>
<td>pyroxenite, picrite, peridotite</td>
</tr>
<tr>
<td>BIF</td>
<td>4</td>
<td>Biwabik Iron-fm (one sample may be the BU Unit)</td>
</tr>
<tr>
<td>BIF Sill</td>
<td>3</td>
<td>Sill in BIF 'C' and 'B'</td>
</tr>
<tr>
<td>AN-G</td>
<td>4</td>
<td>Anorthositic rocks (includes one duplicate sample)</td>
</tr>
<tr>
<td>AN-G</td>
<td>4</td>
<td>Gabbroic rocks (includes one duplicate sample)</td>
</tr>
<tr>
<td>BASALT</td>
<td>5</td>
<td>Inclusions (includes norite and 'norfels' zones)</td>
</tr>
<tr>
<td>gr</td>
<td>4</td>
<td>Late granitic veins associated with the Grano Fault</td>
</tr>
<tr>
<td>GRAN</td>
<td>6</td>
<td>Giants Range granites (includes a duplicate sample); 2 samples are sulfide-bearing</td>
</tr>
</tbody>
</table>
SAMPLING

Geochemical samples were collected from unsplit drill core wherever possible. The intervals sampled range from two to ten feet, with an average thickness of 4-5 feet. Sample numbers represent the drill hole number followed by the footage of the sampled interval, e.g., Du-14 265-270 ft. The drill core was sawn in half (or quartered) by MDNR personnel, and all traces of metal from the saw were later ground off at the NRRI. An attempt was made to sample only homogeneous intervals that were void of: 1) intense fracturing or jointing; 2) pegmatitic lenses with sharp contacts; 3) late granitic lenses with steeply inclined sharp contacts; 4) deuteritic alteration (uralitization); and 5) strong serpentinization (this was somewhat unavoidable within the ultramafic horizons; however, the least serpentinized zones were sampled in these cases). Some of the ultramafic sampled intervals also exhibited rusty chlorine-rich drops that coat the core surfaces. Representative thin section samples were made of all geochemical sample material.

All samples were sent to X-Ray Assay Laboratories (XRAL) in Don Mills, Ontario, Canada; analytical method and detection limits are in the SOKSORT.WK1 file. Three international geochemical standards were submitted for analysis: MRG-1 (referred to as SOK-1); SARM-1 (referred to as SOK-2); and SARM-6 (referred to as SOK-3). Analyzed values, accepted values, and percent difference between the analyzed and accepted values are listed in SOKSORT.WK1 for these standards. As a final precision check, four blind duplicate samples were also included. The duplicate samples were made by sawing the core in half, followed by quartering the halved core and assigning a bogus footage to one of the quartered intervals. In total, 83 samples were sent to XRAL that included three standards and 80 drill core samples (of which four samples were blind duplicates). All 80 drill core samples were also submitted for PGE scans to Dr. Sarah-Jane Barnes, Geology Department, University of Quebec, Chicoutimi, Quebec, Canada. Dr. Barnes ran internal
checks using the Ax90 standard; analyzed values, accepted values, and percent difference between analyzed and accepted values are listed in the SOKSORT.WK1 for this standard.

Notable high values within the analyses include: 1) high Cr values (>400 ppm) are associated with the U1, U2, U3 (maximum of 2,600 ppm), BU, BIF (inclusions), and EXTRA BIF Sill; 2) high TiO2 contents are associated with massive oxide horizons and BIF inclusions; 3) fairly consistently high Pd and Pt values (>100 ppb and >80 ppb, respectively) are associated with the U3 Unit; 4) scattered high Pd and Pt values are associated with the PEG, BH, BAN, BU and GRAN units; 5) elevated Ir, Os, Ru, Rh, and Re values are associated with elevated Pd and Pt values; 6) high Cl values (>1,000 ppm) are associated with the U1, U2, U3, BU, and BIF Sill (one sample) units; and 7) high F values (>300 ppm) are associated with the MAIN AGT, PEG, BAN, gabbros of the AN-G Group, gr (maximum value of 2,150 ppm F), and GRAN units.

SPIDER DIAGRAMS

Plots of chondrite normalized incompatible elements for each of the sampled lithologic units are illustrated on spider diagrams (Figs. 18 to 40). The spider diagrams, and chondrite values used in the normalization, were constructed using the IGPET II program (Carr, 1987), which utilizes the technique outlined by Thompson (1982). Data in the SOKSORT.WK1 file are used in constructing most of the spider diagrams. However, not all of the SKTS units are sampled in this investigation, and thus, data from the DNRSORT.WK1 file are used to construct additional diagrams of the UW, T-AGT, UPPER GABBRO, and “INCL” units. Whenever a value was listed as being less than the detection limit, a value of 0.5 times the detection limit was used in preparing the plots.

Individually, the spider diagram profiles generally show good internal agreement for all the samples collected within a specific major rock group, e.g., the MAIN AGT Unit. Collectively, the profiles are different for each of the major rock groups of the SKTS, e.g., MAIN AGT versus BAN
units. In some cases, these differences are expressed as subtle variations in the profiles. A brief discussion of the spider diagram profiles of the SKTS units is presented below. Whenever possible, the SKTS spider diagram profiles (this investigation) are compared to previously presented PRTS spider diagram profiles (Severson and Hauck, 1990; Severson, 1991). Note that on the spider diagrams, both open and solid triangles are used, these two symbols are not used to designate anything specific--they are a function of the plotting program.

Troctolites of the SKTS

All of the troctolitic units of the SKTS generally exhibit the same gentle slope and pattern on the spider diagrams. However, intra-unit variations are present between each of the SKTS units, which include: 1) Sr peaks are variable and range from positive to flat to negative; 2) Ti peaks are variable and range from flat to highly positive; and most importantly 3) the troctolitic units of the SKTS can be subtly distinguished by their relative position on the spider diagrams, e.g., 'elevated' versus 'decreased' values. For example, the BAN Unit has the most elevated incompatible values in contrast to the UW Unit that has significantly lower incompatible values (Fig. 18). The relative spider diagram positions for each of the fields of the troctolitic SKTS units are compared to each
other in Figure 18. Note that the BAN Unit field plots the highest on Figure 18. It is followed, in decreasing order, by the MAIN AGT, AT(T)/AT&T, troctolites of the U1 and U3, BH, and the UW units. The PEG unit is not shown in this figure because its field is too broad and would complicate this already cluttered diagram. A brief discussion of each of the troctolitic units of the SKTS follows.

**BAN Unit**

The BAN Unit (Fig. 19) plots the highest of all the troctolitic rocks in the spider diagrams (see Fig. 18). Most of the individual profiles are extremely similar, and tight, but exhibit variations in the form of: 1) flat and negative Sr peaks; and 2) flat and positive Ti peaks. There is no correlation between rock type (augite troctolite versus norite) and the type of profiles for samples collected within the BAN Unit. Two samples from the BAN Unit deserve special mention. First, sample NM-6 4126-4130 ft. exhibits a strongly anomalous profile (including a positive Sr peak) when compared to the other BAN profiles. However, in the X-Y plots of the whole rock chemistry (to be discussed later) this same sample is not unique and plots well within the field of all the other BAN samples. Furthermore, another BAN sample also collected from the same drill hole (NM-6 4396-4401 ft.) does not yield an anomalous spider profile. Therefore, it is difficult to ascertain why sample NM-6 4126-4130 ft. is so anomalous, unless it is related to contamination of
the magma. Second, sample B1-171 is from a noritic interval that is in direct contact with footwall rocks at the basal contact. This sample plots the highest in Fig. 19; thus, the elevated values of this sample are possibly related to contamination from the footwall rocks. By analogy, the overall elevated values of the BAN Unit are probably related to magma contamination from assimilated footwall rocks. The spider profiles of BAN units with a negative Sr peak are similar to profiles of Unit I (lower half) of the PRTS.

**Figure 19.** Spider diagram of the BAN Unit.
MAIN AGT Unit

All six samples (including one duplicate sample) collected from the MAIN AGT plot in extremely tight profiles in Figure 20. The only major variant in the profiles are weakly positive to negative Sr peaks. The spider profiles of the MAIN AGT are similar to profiles of Unit I (lower half) of the PRTS and the Powerline Gabbro of the PRI.

Figure 20. Spider diagram of the MAIN AGT Unit.
AT(T) and AT&T Units

Samples collected from the AT(T) (two samples) and the AT&T (two samples) units exhibit the exact same spider profiles (Fig. 21). These two units are very similar in drill core (monotonous zones of texturally homogeneous plagioclase-rich rocks) and cannot be distinguished from each other in the spider diagram. All the samples have extremely tight profiles that exhibit positive Sr and Ti peaks. Their profiles are not similar to any other PRTS spider profiles.
Troctolites of the U1 and U3 Units

Five samples were collected from the intervening troctolitic layers within the ultramafic-bearing U1 and U3 units. Almost all of the samples plot in extremely tight profiles (Fig. 22) with positive Sr peaks, regardless of whether the U1 or U3 units were sampled. Curiously, one of the
samples (NM-43 1052-1056 ft.) exhibits a profile that is remarkably similar to the BAN profiles. This sample was collected from the U3 Unit within 40 feet of the basal contact and, if not for the presence of ultramafic layers, could have easily been classed as BAN. The BAN-type signature for this sample may be related to magma contamination from assimilated footwall rocks. It may also indicate that there is some geochemical overlap between the U3 Unit and the underlying BAN Unit (especially when both are in close proximity to the basal contact). Overall, the profiles of this group are crudely similar to PRTS profiles of Units I (upper half), II, and IV.

Figure 22. Spider diagram of troctolitic layers within the U1 and U3 units.
Figure 23 illustrates the spider profiles for samples collected from the PEG Unit of the SKTS. These samples exhibit the same general negative slope as other SKTS samples, but the profiles do not plot within a tight field. This range of data may be related to the overall heterogeneous nature of the PEG Unit - it contains scattered pegmatitic and pegmatoidal intervals. The overall profile of the PEG Unit is very broad and spans from the BAN field to the field for the troctolites of the U1 and U3 units. Sr values are somewhat variable, resulting in negative to flat to weakly positive Sr peaks. The PEG field is too broad to be accurately compared to spider profiles of the PRTS and other SKTS units.
The sulfide-bearing heterogeneous BH Unit exhibits the same general profiles in all three samples, but the individual profiles do not plot within a tight field (Fig. 24). The profiles have weakly positive Sr peaks; a positive Ti peak is present in only one of the samples. Overall, the
profiles of the BH Unit are similar to Unit II of the PRTS and crudely similar to Unit I (upper half) and Unit IV of the PRTS.

Figure 24. Spider diagram of the BH unit.
The Updip Wedge Unit was not sampled in this investigation. However, data obtained from MDNR reports (in the DNRSORT.WK1 data file) were used to construct the spider diagram. In Figure 25, all four samples plot in a very tight field that characteristically contain the lowest plotted values of all the troctolitic rocks of the SKTS (see Fig. 18). Besides having the lowest values, the profiles are characterized by: 1) an extremely pronounced negative Th peak; 2) positive Sr peak; and 3) positive Ti peak. The profiles of the UW Unit are somewhat similar to profiles of the BH Unit. Comparison of the UW profile to PRTS profiles indicate that the UW is similar to Units I (upper half), II, and IV.
Ultramafic Rocks of the SKTS

All the ultramafic layers of the U1, U2, and U3 units exhibit the same general profiles and slopes on the spider diagrams. Their profiles and slopes are very similar to the troctolitic rocks of
the SKTS (described above), but the ultramafic rocks generally have the lowest incompatible values of any rock type sampled in the SKI (compare Figs. 26 and 27 to Fig. 18). Within this group, the U3 Unit has the highest relative plotted values, and the U2 Unit has the lowest relative plotted values. Overall, the extremely low values for the ultramafic layers as a whole, indicate that they are the most primitive rock type in the entire SKTS stratigraphic section. High MG numbers are associated with the ultramafic layers (see Fig. 41) also substantiate their primitive character.

**U1 and U2 Ultramafic Rocks**

Profiles of eight samples of ultramafic layers (picrite-peridotite) from the U1 (three samples) and U2 (five samples) are shown on Figure 26. Note that the U1 ultramafic rocks generally have higher values relative to the U2 ultramafics. Also, the U1 ultramafic rocks consistently exhibit positive Sr and Ti peaks, whereas the U2 ultramafic rocks have flat to positive Sr and Ti peaks. The profiles of the U1 and U2 ultramafic rocks are somewhat similar to the profiles of ultramafic horizons within Units II, IV, VI, and VII of the PRTS.

**U3 Ultramafic Rocks**

Figure 27 displays the spider profiles for six ultramafic layers sampled from the U3 Unit. As mentioned previously, the U3 ultramafic rocks exhibit the same general slope as the U1 and U2 ultramafic layers, but have the highest values. This relationship may be related to contamination of the U3 Unit due to assimilation of the BIF (the U3 Unit differs from the U1 and U2 units in that it contains BIF inclusions and massive oxide horizons). The U3 ultramafic rocks also exhibit flat to positive Sr peaks (as does the U2) and highly positive Ti peaks. Comparison of the U3 ultramafic profiles with other major rock units indicates that they are similar to profiles of the: U3-massive oxide horizons (Fig. 28); BU Unit of the PRTS (Fig. 29); and BIF (Fig. 30).
Figure 26. Spider diagram of the U2 unit.
Figure 27. Spider diagram of the U3 unit.
U3 Massive Oxide Horizons

Three profiles of massive oxide horizons within the U3 Unit are shown in Figure 28. They are very similar to some of the profiles for the U3 ultramafic rocks, except that the massive oxide horizons exhibit consistently negative Sr peaks and extremely positive Ti peaks.

BU Unit of the Partridge River Intrusion

Because both the BU and U3 units are closely associated with the BIF, profiles of the BU Unit of the PRI are included in this section for comparison with the U3 Unit. The BU Unit is present at the basal contact within a restricted area of the PRI. There, the BU Unit is characterized by olivine cumulates (picrite and peridotite with local massive oxide horizons) that grade down
into coarse-grained orthopyroxenites that grade down into pyroxene-rich, massive-bedded BIF. This relationship suggests that assimilation of the BIF is important to the genesis of the BU Unit. A similar origin is suggested for the U3 Unit, of the adjacent SKI, which also contains BIF inclusions and massive oxide horizons.

Profiles of three samples collected from the BU Unit are depicted in Figure 29. All three rock types exhibit the same general slopes and profiles with negative Sr peaks (plagioclase-poor) and positive Ti peaks (oxide-rich). Their profiles are very similar to profiles obtained for ultramafic layers within the U3 Unit. Also, their profiles are very similar to profiles of BIF samples (Fig. 30). [In fact, one sample was initially sampled

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**Figure 29.** Spider diagram of the BU Unit (within Partridge River intrusion).
from what appeared to be a BU pyroxenite that graded into BIF. However, the profile of this sample indicated that the sample should have been classed as BIF - see the following BIF discussion. The close similarity of the BIF, U3, and BU profiles also indicates that assimilation of the BIF was important in the genesis of the BU and U3 units. Profiles of the BU Unit are not similar to the other ultramafic horizons of the PRTS (within Units II, IV, VI, and VII).

![Biwabik Iron-formation Spider diagram](image)

**Figure 30.** Spider diagram of the Biwabik Iron-formation.

**BIF (Biwabik Iron-formation)**

Four samples of the footwall BIF were selected from three different textural varieties, which include: 1) massive-bedded, pyroxene-rich iron-formation (two samples); 2) magnetite-rich, well-
bedded iron-formation; and 3) recrystallized, pyroxene-rich iron-formation with rare thin magnetite beds (originally logged as the BU Unit, but the spider profile of this sample shows an almost identical match with the other BIF profiles). The stratigraphic position of the four BIF samples is unknown because a complete section of BIF is not present in the sampled drill holes. Profiles of all four samples are shown in Figure 30. Note that three of the samples display very similar profiles regardless of the variety of rock type sampled (including the recrystallized BIF that was originally classed as the BU Unit). Also note that the two pyroxenite-rich BIF profiles are dissimilar. This dissimilarity may be because they reflect two different submembers of the BIF.

Comparison of the BIF to the U3 and BU units indicates that all three profiles are very similar, except for the extremely negative Sr peaks associated with the BIF. This relationship indicates that assimilation of the BIF is important in the genesis of the BU and U3 units of the PRI and SKI, respectively. Note that three of the BIF samples have positive Ti peaks (1.37%-4.19% TiO₂) related to the metasomatic transfer of Ti across the basal contact from the Complex. The average TiO₂ content of the BIF located well to the west and distant from the Complex is much lower—0.12% TiO₂ (Morey, 1992).

**Highway 1 Corridor Rocks**

Spider diagrams for some of the major rock units associated with the Highway 1 Corridor rocks include: 1) anorthositic layers from the AN-G Group (Fig. 31); 2) gabbroic layers from the AN-G Group (Fig. 32); 3) T-AGT Unit (Fig. 33); and 4) UPPER GABBRO Unit (Fig. 34); the latter two units were not sampled in this investigation. Data for the latter two units are from MDNR reports (DNRSORT.WKI file in back pocket). Most of the profiles for these HIC units plot in tight fields, except the UPPER GABBRO Unit (which exhibits extremely positive P peaks). The profiles for each of these units are dissimilar, except for the ‘gabbros of the AN-G’ and T-AGT units.
Profiles for the ‘gabbros of the AN-G’ are similar to the MAIN AGT Unit of the SKTS. In addition, the profiles for the ‘gabbros of the AN-G’ are similar to profiles obtained for PRI rock units that include Unit I and the Powerline Gabbro.

Figure 31. Spider diagram of anorthositic rocks from the AN-G GROUP.
Figure 32. Spider diagram of gabbroic rocks from the AN-G GROUP.
Figure 33. Spider diagram of the T-AGT unit (data from MDNR analyses).
Figure 34. Spider diagram of the UPPER GABBRO Unit (data from MDNR analyses).

Late Granitic and Pyroxenitic Lenses (gr)

Four samples of late granitic to pyroxenitic material from two drill holes (B1-169 = 1 sample, and B1-431 = 3 samples) in the vicinity of the Grano Fault are plotted in Figure 35. In every case,
Figure 35. Spider diagram of late granitic/felsic lenses (gr) from the Grano Fault area within the Partridge River.

these rocks occur as steeply inclined lenses that cross-cut the troctolitic rocks of the SKTS. In some
cases, a variety of different rock types are present within a short drill core interval; three such
varieties were collected from BI-431. The samples analyzed are: 1) two granitic lenses (both
samples are from BI-431); 2) a hornblende-rich (>80%) monzodiorite lense; and 3) an oxide-apatite
bearing pyroxenite that is similar to the OUIs (from BI-169). Figure 35 displays the profiles for all
four samples. Two different profile trends are apparent. The three samples collected from Bl-431 (granitic and monzodiorite samples) plot in a fairly tight field, but minor differences are apparent for the monzodiorite. In contrast, the pyroxenite sample (OUI) displays a remarkably different pattern characterized by extremely high values for Nd, P, Sm, Ti, Tb, Y, Tm, and Yb. Comparison of the late granitic pattern to other rock pattern indicates that they are similar to patterns of the Giants Range granitic rocks. The pyroxenite pattern is remarkably similar to the late OUIs in the nearby Babbitt deposit area (Severson, 1991). However, the pyroxenite pattern is not similar to the oxide-rich OUIs in the Longnose-Longear-Section 17 area (Severson and Hauck, 1990). This difference suggests two patterns for the OUIs as a group, which includes: 1) oxide-rich OUIs (Longnose-Longear-Section 17); and 2) oxide-poor to oxide-bearing OUIs (Babbitt deposit and Grano Fault area). The different patterns may also suggest that the two OUI types may have originated via different modes of formation and/or different magmatic events or from different source rocks. Unfortunately detailed geochemistry on the vast amounts and types of OUIs is lacking to sufficiently address these differences.

**Inclusions of Hanging Wall Rocks**

There are two different types of hanging wall inclusions, which include: basalt inclusions (five samples--massive to vesicular, fine-grained, granular rock); and Colvin Creek (CC) type material (two MDNR samples for the ‘INCL’ in the Highway 1 Corridor).

**Basalt Inclusions**

Figure 36 displays the profiles for five samples collected of basalt inclusions from the Serpentine and Babbitt areas. In the Serpentine area, the basalts are characterized by fine-grained, granular rock (± vesicles) that grades vertically and laterally into weakly recrystallized basalt
(referred to as ‘norfel’). The basalts also grade into strongly recrystallized basalt that was often improperly logged as norite. The latter observation was unknown at the time the initial rock samples were collected. A ‘norite’ collected from an interval in direct contact with a basalt inclusion is an almost exact match to two profiles of basalt inclusions (see Fig. 36).

Two slightly different groups of profiles for the basalt inclusions are apparent in Figure 36. The reason for this grouping is unknown. The groups are not related to the type of material sampled, the degree of recrystallization, nor the stratigraphic height of the inclusion relative to the basal contact. Also, they are not related to geographic location of the sampled drill hole (Serpentine area versus Babbitt area). Comparison of the Figure 36 patterns to other previously sampled inclusion types indicates the following: 1) the top two profiles are similar to profiles of the ‘INCL’ Unit of the HIC; and 2) the bottom three profiles are similar to basalt and CC-type inclusions present in the Babbitt deposit area (Severson, 1991).
Figure 36. Spider diagram of basalt inclusions in the South Kawishiwi and Partridge River intrusions.
‘INCL’ of the H1C
The ‘INCL’ is characterized by moderately to strongly-magnetic, fine-grained, granular rocks that locally exhibit vesicle-like features (Fig. 37). In drill core, the ‘INCL’ often resemble the CC-type material found elsewhere (Severson, 1991; Severson and Hauck, 1990). However, these ‘INCL’ patterns are not similar to profiles of other CC inclusions (Severson, 1991). Rather, their
profiles are similar to some of the basalt inclusion patterns described previously. X-Y plots of major elements (discussed later) further compound this problem. On these plots, two distinctly different ‘INCL’ and basalt fields are evident. Clearly, additional work is needed to fully understand the differences between inclusions of the CC-type (or ‘INCL’) and the basalt-type within the PRI and SKI.

Footwall Rocks

Biwabik Iron-formation (BIF)

Profiles of the BIF are displayed in Figure 30. The similarity of the BIF profiles to profiles of the U3 and BU units has been previously discussed.

BIF Sill

Within this report, the term ‘BIF Sill’ refers to a granular-textured, fine-grained sill that is present within the C submember of the BIF. In the Serpentine deposit area, similar-looking, but extremely fine-grained, chilled sills are also present within the A and B submembers of the BIF; they are referred to as ‘EXTRA BIF Sills’ in this report. Both sills are granular-textured and have been metamorphosed by the Duluth Complex. They are, therefore, inferred to have been emplaced prior to intrusion of the PRI and SKI and may be time synchronous with the Logan Sills that are exposed to the east along the northern contact of the Complex. All samples of the BIF Sill (Fig. 38) plot in a very tight field that is characterized by a negative Sr peak and a weakly positive Ti peak. Note that the four samples of BIF Sill are from drill holes in the Peter Mitchell Mine area, Serpentine deposit area, and the Dunka Pit area (all within a 3 mile strike length). In contrast, the EXTRA BIF Sill (one sample), also collected from a drill hole in the Serpentine deposit area, displays an entirely different profile that is characterized by a positive Sr peak and nonexistent Ti peak. In addition,
the profile of the EXTRA BIF Sill is remarkably similar to profiles of the VIRG Sill (Fig. 39), which is also inferred to have been emplaced prior to intrusion of the PRI and SKI.

Figure 38. Spider diagram of the BIF Sill and EXTRA BIF Sill.

The similarity of the profiles for the VIRG Sill and EXTRA BIF Sill suggest that the two are related. The original interpretation of the EXTRA BIF Sill is that it formed from BIF Sill material that intruded upward into the A and B submembers of the BIF along the trace of the Grano Fault
in the Serpentine deposit area. However, the similarity in spider profiles suggests that this interpretation may be incorrect. Instead, the VIRG Sill may have intruded down to form the EXTRA BIF Sill along the trace of the Grano Fault. Furthermore, X-Y plots of whole rock chemistry (to be discussed, p. 150) also suggest that the VIRG Sill and EXTRA BIF Sill are similar (both also contain Cr in excess of 400 ppm).

Figure 39. Spider diagram of the VIRG Sill (data from Severson, 1991, and MDNR).
In summary, the BIF Sill is chemically different from either the EXTRA BIF Sill or VIRG Sill. The VIRG Sill and EXTRA BIF Sill are chemically similar. This suggests that the BIF Sill and VIRG Sill may have been emplaced during two separate events (both time synchronous with the Logan Sills?). In general, the BIF Sill is Cr-deficient and the VIRG Sill (and the chilled EXTRA BIF Sill) is Cr-bearing (400-2,300 ppm).

Granitic Rocks of the Giants Range Batholith

Spider plots of five samples (including one duplicate) of various granitic rocks of the Giants Range Batholith (GRAN) are displayed on Figure 40. All samples, regardless of rock type and sulfide content, plot in a very tight pattern. Contaminated zones (referred to as "cn") have not been sampled, and therefore, the difference between ‘fresh’ rock and ‘contaminated’ rock is not addressed in this report.
Figure 40. Spider diagram of granitic rocks from the Giants Range Batholith beneath the Duluth Complex.

**X-Y SCATTER PLOTS**

X-Y scatter plots of MgO versus various whole rock values are presented in Figures 42 through 45. A plot of MG Number versus Al₂O₃ is shown in Figure 41. Values used in plotting the
VIRG Sill are from Severson (1991). All sample points are plotted using IGPET II (Carr, 1987), which normalizes the major oxides to 100% on a water free basis; trace element values are not normalized. All of the individual data points are shown on the X-Y plots that were prepared using the SOKSORT.WK1 file. These are generally the Figure-A plots of this report, e.g., Figure 41-A. Conversely, only the fields are shown on the X-Y plots that were generated using previously collected samples (from DNRSORT.WK1 data). These are always the Figure-B plots in this report, e.g., Figure 41-B. In both cases, distinct fields for the various rocks units are apparent on the scatter plots. Whenever possible, these fields are outlined on the accompanying figures (A & B) and are briefly discussed below. There is always very good agreement between the fields on the Figure-A plots to the corresponding fields on the Figure-B plots; however, the fields on the Figure-B plots are generally much broader because they are based on a larger amount of data points. The fields of the Giants Range Batholith (GRAN) and late granitic/felsic lenses (gr) are not portrayed on all the X-Y plots.
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Figure 41-A. MG number versus $\text{Al}_2\text{O}_3$: Data from this investigation.
Figure 41-B. MG number versus Al$_2$O$_3$: Data from previous analyses.
Figure 42-A. MgO versus CaO: Data from this investigation.
Figure 42-B. MgO versus CaO: Data from previous analyses.
Figure 43-A. MgO versus SiO₂. Data from this investigation.
Figure 43-B. MgO versus SiO$_2$: Data from previous analyses.
Figure 44-A. MgO versus FeO* (FeO* = FeO + 0.8998 Fe$_2$O$_3$): Data from this investigation.
Figure 44-B. MgO versus FeO* (FeO* = FeO + 0.8998 Fe₂O₃): Data from previous analyses.
Figure 45-A. MgO versus TiO$_2$: Data from this investigation.
Troctolites of the SKTS

All of the troctolitic rock units of the SKTS show a good cluster on the X-Y plots (their field is referred to as ‘troctolites’). The SKTS units in this category include the following: AT(T); AT&T; MAIN AGT; BH; PEG; and troctolitic layers within the U1 and U3. The AT(T) and AT&T units plot on the left end of the ‘troctolite’ field (more evolved rocks). The MAIN AGT plots in the center of the field, and the BH and U1-U3 troctolites plot in the right two-thirds of the field. PEG Unit samples are scattered throughout the ‘troctolite’ field. The BAN Unit samples cluster in a separate field that partially overlaps with the ‘troctolite’ field. All of the above observations apply to both the A and B figures.
Whole rock chemistry cannot be used to distinguish the troctolitic rocks of the SKTS because they cluster in tight and overlapping areas on the X-Y plots. The units of the PRTS also cluster in the same general areas on similar X-Y plots in Severson and Hauck (1990), and Severson (1991).

Ultramafic Layers of the SKTS

The ultramafic layers of the SKTS also show a good clustering toward the right side of the X-Y plots. This group includes ultramafic layers from the U1, U2, U3, and BU units. They plot in a separate, more primitive field (higher MgO content) than the troctolitic rocks. A differentiation trend is suggested by the linearity between the primitive ultramafic layers and the more evolved troctolitic rocks. Some of the most primitive rocks of this ultramafic group are from the U2 Unit (the three samples on the extreme right of the plots). Otherwise, the U1, U2, U3, and BU ultramafics are scattered throughout the field that defines the ultramafics. These ultramafic layers plot within the same field as ultramafic horizons of the PRTS (Severson and Hauck, 1990; and Severson, 1991).

Samples collected from massive oxide horizons present within the U3 Unit are also shown on the X-Y plots. They plot in a separate field that shows considerable overlap with the BIF (except in the MgO versus TiO₂ plot).

Highway 1 Corridor Rocks

The fields of four of the major rock units of the H1C are shown on Figures 41-45. The anorthositic rocks plot in a separate field at the extreme left side of the X-Y plots (low MgO contents - most evolved). The field for the gabbroic rocks of the AN-G Group plot in a separate
field that is distinct from the anorthositic rocks and often shows some overlap with the troctolitic rocks of the SKTS.

Late Granitic and Pyroxenitic Lenses (gr)

Rocks of the ‘gr’ group are shown on both the Figure-A and Figure-B (Figs. 41-45) plots. The samples plot in a field that often overlaps with the field for granitic rocks of the Giants Range Batholith (GRAN). Some samples (monzodiorite and pyroxenite) plot as isolated scattered points. However, these rock types generally lie within the OUI field reported in Severson and Hauck (1990).

Inclusions of Hanging Wall Rocks

Basalt inclusions within the SKI cluster within distinct and small fields that are coincident in both Figure-A and Figure-B plots. The basalt inclusion fields are also coincident with the basalt inclusion field in Severson (1991). Two samples of the ‘INCL’ are shown in only the Figure-B plots. They are not coincident with the basalt inclusion field.

Footwall Rocks

Fields that define the Biwabik Iron-formation (BIF) are, in some cases, very broad fields and indicate the diverse geochemical variation of the various submembers of the BIF. Fields for both the BIF and U3-massive oxide horizons show considerable overlap. Granitic rocks of the Giants Range Batholith (GRAN) are shown for comparison to all the other rock units in only Figure 43.

On Figures 41-45 (A and B), the BIF Sill samples cluster in a tight field that is distinct and separate from the EXTRA BIF Sill and VIRG Sill samples. The latter two sill types plot as a linear
function on the X-Y plots that is suggestive of a differentiation trend. Overall, the BIF Sill group is chemically distinct from the EXTRA BIF Sill-VIRG Sill group.

AFM DIAGRAM

All rock types of the SKTS plot within the tholeiitic field on AFM diagrams (Figs. 46-A and 46-B). There is some overlap into the calc-alkaline field (especially samples of anorthositic rocks from the AN-G Group of the HIC). Granitic rocks of the Giants Range Batholith (GRAN) and late granitoidal rocks (gr) are all calc-alkaline in composition.
Figure 46-A. AFM diagram: Data from this investigation (*FeO - total iron as FeO).

Figure 46-B. AFM diagram: Data from previous analyses (*FeO - total iron as FeO).
SULFUR ISOTOPE STUDIES

Figure 47. Schematic diagram showing relationships of samples collected for sulfur isotope analyses.

Sulfur isotope values for 15 samples of various sulfide-mineralized rock from drill core and pit exposures are listed in Table 2 (analyzed by Dr. E. Ripley, Indiana Univ.). The geologic setting of these samples is illustrated on Figure 47. In many cases, the massive sulfides in the SKI are spatially related to areas where the BDD PO member of the Virginia Formation is present at the basal contact or as inclusions. This empirical relationship suggests that the BDD PO member may have represented an excellent local sulfur source for the nearby sulfide-mineralization in the SKI. Sulfur isotope analyses of the BDD PO member range from 14.0 to 21.1 per mil (Table 2), and
illustrate the isotopic variability of the sulfides in this member. Similar values, 15.3 to 29.1 per mil, are reported for the BDD PO member within the Serpentine Cu-Ni deposit (Zanko et al., 1994). Such heavy values have not been obtained from other portions of the Virginia Formation (Ripley, 1981; Ripley and Al-Jassar, 1987). Samples collected from disseminated and massive sulfide mineralization (Table 2) in the SKI, BIF, and GRAN units show a very limited range of values that range from 8.7 to 12.4 per mil. These values are higher than typical magmatic values and suggest that some contamination has occurred due to addition of sulfur from an external source. Similar sulfur isotope values have been obtained from massive sulfide and disseminated sulfide mineralization in the Babbitt deposit of the PRI (Ripley and Al-Jassar, 1987). There, the sulfur isotope data suggest that most of the sulfur has been derived from sedimentary country rocks; however, an in situ process was not indicated (Ripley and Al-Jassar, 1987). The vast difference in sulfur isotope values for the BDD PO member relative to nearby massive sulfide zones in the SKI also suggest that an in situ process was not operational. This is in contrast to the empirical/spatial relationships previously mentioned. However, sulfur isotope studies of, specifically, the BDD PO member have been extremely limited (this investigation; Zanko et al., 1994), and the complete range of sulfur isotope values have not been fully established. Additional sampling of the BDD PO member may indicate that it also contains values on the order of 8.0 to 10.0 per mil, which would be comparable to the values in the nearby SKI. Thus, before an in situ process is completely ruled out, additional sampling of the BDD PO member is prudent.
Table 2. List of sulfur isotope samples and results.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Description</th>
<th>Unit</th>
<th>Sulfur Isotope (per mil)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP-1</td>
<td>Dunka Pit grab sample of augite troctolite with 1-3% sulfides</td>
<td>BH</td>
<td>9.5 (Chalcopy) 9.0 (Pyrrhotite)</td>
</tr>
<tr>
<td>D-2 1577 ft.</td>
<td>Norite with 1-2% sulfides (Cp&gt;Po); 3 feet above basal contact</td>
<td>BAN</td>
<td>11.1</td>
</tr>
<tr>
<td>D-9 1292 ft.</td>
<td>Norite with 0.5% sulfides (Po&gt;Cp); 5 feet above basal contact</td>
<td>BAN</td>
<td>12.4</td>
</tr>
<tr>
<td>DP-2</td>
<td>Dunka Pit grab sample of BDD PO member</td>
<td>Virg. Fm.</td>
<td>21.1</td>
</tr>
<tr>
<td>D-13 385 ft.</td>
<td>Inclusion of BDD PO member 10% pyrrhotite</td>
<td>Virg. Fm.</td>
<td>18.4</td>
</tr>
<tr>
<td>B2-9 789 ft.</td>
<td>Inclusion of BDD PO member 5% pyrrhotite</td>
<td>Virg. Fm.</td>
<td>14.0</td>
</tr>
<tr>
<td>PM-1</td>
<td>Peter Mitchell Mine grab sample of massive sulfide pod near the basal contact</td>
<td>BAN?</td>
<td>12.3</td>
</tr>
<tr>
<td>D-9 1282.5 ft.</td>
<td>Massive sulfide (&gt;90% Po) within norite; 15 feet above basal contact</td>
<td>BAN</td>
<td>11.5</td>
</tr>
<tr>
<td>E-9 1575 ft.</td>
<td>Massive sulfide (&gt;95% Po) within aug troct; 15 feet above basal contact</td>
<td>BAN</td>
<td>11.4</td>
</tr>
<tr>
<td>B2-9 789 ft.</td>
<td>Massive sulfide within a noritic zone with abundant Virg. Fm. inclusions</td>
<td>BH</td>
<td>11.5</td>
</tr>
<tr>
<td>D-9 1249 ft.</td>
<td>Massive sulfide (&gt;95 Po) within BIF incl.; 191' feet above basal contact</td>
<td>BH</td>
<td>10.2 (Pyrrhotite) 10.6 (Cubanite)</td>
</tr>
<tr>
<td>D-2 1584 ft.</td>
<td>Contaminated' zone with 2-3% fnly dissem sulfides (Cp&gt;Po) 4 feet below basal contact</td>
<td>GRAN</td>
<td>9.7</td>
</tr>
<tr>
<td>D-2 1588-1589 ft.</td>
<td>Massive sulfide (&gt;90% Po); 8 feet below basal contact</td>
<td>GRAN</td>
<td>8.7</td>
</tr>
<tr>
<td>D-5 1620 ft.</td>
<td>Massive sulfide (&gt;90% Po) in 'contaminated' zone; 25 feet below basal contact</td>
<td>GRAN</td>
<td>10.7</td>
</tr>
<tr>
<td>D-12 1290 ft.</td>
<td>Massive sulfide (&gt;70% Po); 24 feet below basal contact</td>
<td>GRAN</td>
<td>10.4 (Pyrrhotite) 11.4 (Chalcopy)</td>
</tr>
</tbody>
</table>

PGE SCANS
Eighty pulp samples were submitted for PGE scans (Pt, Pd, Ir, Ru, Rh, Re, and Au) to Dr. Sarah-Jane Barnes, Geology Department, University of Quebec, Chicoutimi, Quebec, Canada. The pulps were prepared by XRAL. PGE analytical procedures are outlined in Barnes and Giovenazzo (1990).

Out of the 80 samples (data in SOKSORT.WK1), 10 samples contained >100 ppb Pd from the following units: BAN - 1 sample with 1,032 ppb Pd and 419 ppb Pt; PEG - 2 samples with a maximum 366 ppb Pd and 136 ppb Pt; and U3 - 7 samples with a maximum 436 ppb Pd and 277 ppb Pt (this set includes one troctolite layer, two massive oxide layers, and four ultramafic layers from the U3 Unit). Pt/Pd ratios for these 10 samples vary from 1:1 to 1:3.5, with an average of 1:2. All the other SKTS samples have Pt/Pd ratios that vary from 1:3 to 3:1 with an average of 1:1. In general, samples with elevated Pd values also contain elevated values of Pt, Ir, Ru, Rh, Re, and Au.

Figures 48, 49, and 50 are a compilation of all SKI samples with complete PGE scan analyses. Data used to construct these figures are from: 1) analyses conducted in this investigation (SOKSORT.WK1); 2) analyses from MDNR reports and MDNR open files (listed in SOKAWR.WK1 and SOKAPM.WK1); 3) analyses from the Serpentine deposit (Zanko et al., 1994); 4) analyses from the South Filson Creek deposit (Kuhns et al., 1990); and 5) analyses from the Birch Lake area (Sabelin and Iwasaki, 1986; Mogessie and Stumpfl, 1992). All of these plots were originally developed by Dr. Sarah-Jane Barnes as possible exploration tools to help define intrusions with potential for a PGE deposit (Barnes, 1990; Barnes et al., 1990).
Figure 48. Plot of Cu/Pd versus Pd.

Figure 49. Plot of Ni/Pd versus Cu/Ir.
The plot of Cu/Pd versus Pd (Fig. 48) was developed by Dr. S.-J. Barnes as a means of evaluating when sulfide segregation occurred, and evaluating subsequent changes to the segregation during and after emplacement of layered intrusions (Barnes et al., 1990). In this manner, the inter-element ratios (Cu/Pd) for a particular deposit can be compared to mantle ratios (6 x 10³ for Cu/Pd) to determine if a layered intrusion has potential for hosting a PGE reef deposit. Figure 48 is broken into three fields: 1) 'depleted' relative to mantle ratios; 2) 'enriched' relative to mantle ratios; and 3) a neutral field that roughly corresponds to mantle ratios (unmarked area between the 'depleted' and 'enriched' fields). The Cu/Pd ratios of PGE reef deposits (Merensky Reef, J-M Reef, etc.) plot within the enriched field, and the Cu/Pd ratios of Cu-Ni deposits (Sudbury, Duluth Complex, etc.) plot within the depleted field (Barnes et al., 1990). On Figure 48, most of the samples from the SKI plot within the depleted field, except for some samples from the U3 and PEG units. The Cu/Pd ratios for samples that plot in the depleted field may be high because: 1) there was a low concentration of PGEs in the original mantle melt; 2) the PGEs had been removed by a previous sulfide segregation prior to emplacement that impoverished the rocks with respect to PGEs; 3) Cu was added to the magma through contamination of the magma by assimilation of footwall rocks; or 4) the Cu/Pd ratios are high due to Cu ± PGE redistribution by hydrothermal fluids. However, there are also numerous samples of the U3 and PEG units that plot within the neutral field and enriched field (specifically, within the 'PGE-dominated deposit' field). This relationship indicates that the rocks within the lower part of the SKTS (U3 and PEG) have some potential for hosting a PGE reef deposit. It is also important to note that both U3 and PEG samples show a scattering of plotted points on Figure 48 that span from the enriched into the depleted field. This observation suggests that the Cu/Pd ratios within the U3 and PEG have been altered - possibly due to redistribution by hydrothermal fluids.
The plot of Ni/Pd versus Cu/Ir is shown in Figure 49. In this figure, if a sample plots below the field that defines extrusive rocks, it suggests a potential for forming a PGE deposit. However, Dr. Barnes states that, 'Rocks formed from magma depleted in PGE by an earlier sulphide segregation will plot above the field of extrusive rocks defined by komatiites, high-MgO basalts and flood basalts. Such rocks do not make good exploration targets, they do however suggest that PGE-enriched rocks might lie stratigraphically below them. It should also be remembered that if each cyclic unit in an intrusion represents a new influx of magma the process may be repeated several times.' (Barnes, 1990, p. 10) In reviewing Figure 49, rocks that plot below the field that define extrusive rocks, and potentially could form a PGE reef deposit, are associated with the U3 and PEG units of the SKTS.

The same explanation applies to the plot of Pd/Ir versus Ni/Cu (Fig. 50). If a sample plots above the field that defines extrusive rocks, and within the PGE-reef field, it suggests a potential for forming a PGE deposit. However, in Figure 50 very few samples of the SKI are in this category.

In summary, all three of above figures indicate that the lowest units of the SKTS (U3 and PEG units) could potentially have formed a PGE deposit. However, the data also indicate that hydrothermal fluids could have redistributed the Cu and PGEs in all units of the SKTS (including U3 and the PEG Unit).
Figure 50. Plot of Pd/Ir versus Ni/Cu.
INTRODUCTION

From the discussion in the previous chapter, the U3 Unit, and to a lesser extent the PEG Unit, show the most promise of hosting a PGE deposit. A review of all the analytical data on the SKI reveals that the vast majority of "anomalous" (>100 ppb) Pd and Pt values are associated with the U3 Unit (Fig. 51). The maximum values obtained from the U3 are 5,482 ppb Pd and 4,461 ppb Pt. Because all the data indicate that the U3 and PEG units are the most interesting with regard to PGE potential, the following discussion will be constrained to these two units.

Initially, high PGE values were only known to be present within drill hole Du-15 (Sabelin and Iwasaki, 1986). Several anomalous values are found scattered throughout the bottom portion of the hole, but the highest values are from a 30 foot thick zone that averages >2 ppm combined Pt+Pd. A maximum value of 9,123 ppb combined Pt+Pd is associated with this zone; the Pt to Pd ratio is near one over the entire zone (Sabelin et al., 1986). In Du-15, the high Pt and Pd values correlate closely with a depletion in Cu and an enrichment in Cr that ranges from 1.9 to 5.3% (Sabelin and Iwasaki, 1986). Rock types associated with the mineralized zone consist of massive oxides and oxide-bearing ultramafic layers within the U3 Unit. Platinum group minerals occur
mainly as inclusions within plagioclase associated with oxide grains (Sabelin and Iwasaki, 1986). Several other massive oxide horizons in the U3 Unit are intersected in Du-15, but none of these horizons contain similarly high Pt and Pd values. Chlorine-rich liquid drops coat the drill core about 55 feet above the mineralized zone. The major oxide within all the massive oxide horizons is coarse-grained, rounded magnetite, with varying amounts of ilmenite lamellae parallel to (111), ulvospinel (tentative identification) lamellae parallel to (111), and extremely fine, cloth-like nets of spinel (tentatively identified as ulvospinel and hercynite/green pleonaste) parallel to (100). The fine cloth-like nets are present within the cores of most magnetite grains. Mineral chemistry studies of the oxides (Sabelin and Iwasaki, 1985) from the mineralized zone indicated that they have high TiO$_2$ contents (6-12%) and variable contents of MgO (1-3%), Al$_2$O$_3$ (2-6%), and Cr$_2$O$_3$ (up to 10%). Hercynite (or green pleonaste) is also found associated with the oxides and occurs as coarse round blebs adjacent to magnetite grains (Sabelin et al., 1986; Alapieti, 1991). Alapieti (1991) reports that the magnetite grains are typically welded, or sintered, and often form coalesced grains arranged in atoll-like textures. He feels that they formed by sintering/annealing of magnetite grains derived from intruded and assimilated BIF. The sintered atoll-like magnetite grains are commonly enclosed in coarse-grained, poikilitic plagioclase, and to a lesser extent, in poikilitic olivine. Alapieti (pers. comm.) refers to this texture in thin section as a ‘2 in 1 rock’ because it looks as if the texture is the result of two different thin sections superimposed on each other. This ‘2 in 1’ texture is most commonly found within the 30 foot thick PGE mineralized zone of Du-15.

In an attempt to duplicate the PGE values found in drill hole Du-15, the MDNR conducted a sampling campaign on several drill holes (Dahlberg, 1987; Dahlberg et al., 1989). During this time, drill hole Du-9 was also found to contain a few high PGE values within two intervals. Maximum values in Du-9 are 2.8 ppm Pt and 1.3 ppm Pd (Dahlberg, 1987). Both of the anomalous intervals are associated with, and adjacent to, a Cr-bearing (16,000 ppm) oxide-rich plagioclase-pyroxene hybrid
rock with a ‘2 in 1’ texture within the PEG Unit. Exploration companies also conducted sampling campaigns on several holes that exhibited a similar geologic setting to Du-15. Sampled intervals generally consisted of massive oxide horizons associated with ultramafic horizons; chlorine-rich drops were associated with some of these zones. Drill holes sampled during these campaigns included: Bl-68, Du-12, Du-14, Du-16, 34872 and Du-9W (wedged from the bottom of Du-9). Platinum and palladium values up to a few hundred ppbs were found in some of these holes (see SOKAWR.WK1 and SOKAPM.WK1), but the values never equalled the Du-15 occurrence.

During 1988 through 1990, several holes were drilled within the vicinity of Du-15 (referred to as the Birch Lake deposit in this report; a cross-section of the area is illustrated in Plate XI). Holes that were drilled include: C-88-1, BL-89-1, BL-89-2, BL-90-1, BL-90-2, and BL-90-3 (located a few miles north of the Birch Lake deposit). Two wedged holes were also drilled and include D15-W1 (wedged from Du-15) and BL-90-3W (wedged from BL-90-3). All of these new drill holes intersect the U3 Unit in the bottom portions of the holes. In all instances, the U3 Unit contains variable amounts of oxide-bearing ultramafic layers + massive oxide horizons. High Cr values (>300-400 ppm) are always associated with the U3 Unit. Some of the holes have common Pd values in excess of a few hundred ppbs, but values that equal the Du-15 occurrence are only duplicated in BL-89-1, BL-89-2, and BL-90-1 (note analytical results for BL-90-2 were not open filed at the MDNR during the report period). The highest values encountered in this group of holes are from BL-89-1 which has 4,189 ppb Pt and 4,652 ppb Pd over a 2.5 foot thick interval (see SOKAPM.WK1). Unlike the Du-15 occurrence, the high Pt and Pd values in these drill holes are associated with: some sulfide-bearing troctolitic layers; some sulfide and oxide-bearing ultramafic layers; some pegmatitic zones; and some massive oxide horizons.

GEOLOGY AND MINERALIZATION AT THE BIRCH LAKE DEPOSIT
The overall geology of the PGE-bearing portion of the Birch Lake deposit (BLD) is shown in Plate XII, which is a hung cross-section that is horizontally compressed. This plate is constructed by plotting the lower most portions of all the BLD holes at a 1 in. = 20 ft. scale (vertical scale only), and hanging the holes on the top of the U3 Unit. In this manner, the various internal layers of the U3 are able to be correlated between widely spaced drill holes, and a crude overall geological picture of the U3 is, therefore, approximated. In viewing the geological correlations displayed in Plate XII, several features are apparent. First, pegmatitic zones are common to the overlying PEG Unit, but pegmatitic zones/layers are also locally present in the top portion of the U3 Unit. Second, the amount and relative thicknesses of ultramafic layers intersected in any particular drill hole is highly variable. Note that some of the individual ultramafic layers of the U3 Unit are portrayed as being correlative between the drill holes. This correlation may be an erroneous situation, but it has been retained in this report as a means of comparing the geology between widely spaced drill holes. Third, the massive oxide horizons of the U3 Unit are extremely variable in terms of the number of horizons intersected in a particular drill hole. In addition, the massive oxide horizons are not always present at the same relative stratigraphic position within the U3. Drastic thickness changes for massive oxide horizons between even close-spaced drill holes is also indicated. This thickness variation is most evident in drill hole Du-15 and its nearby wedged hole, D15-W1 (Plate XII). All of these relationships suggest that the massive oxide horizons are actually dissociated pods that are ‘floating’ within the U3 Unit. Fourth, medium- to coarse-grained pyroxene-rich rocks (pyroxenite and melagabbro) are tentatively referred to as inclusions of “BIF?”. These rocks are void of any bedding features, but because they are commonly present at the basal contact they may represent hybridized portions of the BIF. Finally, drill hole BL-90-2 is the most unique in that it encountered very few ultramafic layers and no massive oxide horizons within the U3 Unit. Drill hole BL-90-2 is also unique in that it intersected several zones of a hybrid rock that
consist entirely of varying amounts of saussuritized plagioclase, uralite (a mixture of various amphiboles and chlorite), K-spar, and quartz. The hybrid zones exhibit gradational contacts with the surrounding troctolitic rocks. Near vertical granitic veins are commonly found within the hybrid zones. These relationships suggest that the hybrid zones could be related to a metasomatic replacement mechanism related to upward streaming fluids. These fluids could have originated from either filter-pressed, evolved intercumulus fluids or from fluids generated through partial melting of the footwall rocks.

Chlorine-rich liquid drops commonly coat the drill core of various rock types of the U3 Unit. These drops form via a deliquescent process on drill core that has an initial high Cl content. The distribution of Cl-rich drop coated drill core is also shown on Plate XII. For the most part, the drops coat intervals of massive oxide and ultramafic rocks. However, not all massive oxides and ultramafic layers have Cl-rich drops. In addition, the stratigraphic position of zones with Cl-rich drops is not consistent within the U3 Unit. These relationships indicate that a random distribution pattern aptly describes these zones of Cl-rich drop-coated drill core.

Individual sulfide-bearing zones are not shown on Plate XII because all of the rocks of the U3 Unit are sulfide-bearing. Sulfide content ranges from trace amounts to about 3% by volume. The massive oxide horizons always contain some sulfides, but in general they have lesser amounts relative to the troctolitic and ultramafic layers. Chalcopyrite and pyrrhotite are the most evident sulfides in drill core. They are present in near equal amounts, except near the basal contact where pyrrhotite is the dominant sulfide. In thin section, the sulfides occur as intercumulus minerals that are often cut by secondary magnetite stringers (the magnetite stringers are the product of serpentinization). Secondary sulfides, indicative of a sulfide remobilization event, are also present in some thin section samples collected from the U3 Unit. These are characterized by: bornite, chalcocite, and mackinawite that replace sulfides; and chalcopyrite-filled micro-cracks that branch
out from the earlier intercumulus sulfides and cross-cut silicate grains. In some instances, the micro-cracks locally cross-cut the secondary magnetite stringers.

The distribution of anomalous Pt+Pd zones (≥ 1 ppm) and anomalous Cr zones (≥ 800 ppm) are also portrayed on Plate XII. Thus these two anomalous zones can be compared to each other and to the relative rock types with which they are associated. Most of the high Cr zones are associated with either massive oxide horizons or oxide-bearing ultramafic layers. The reverse is not true; however, not all massive oxides contain high Cr values. Overall, zones with a high Cr content are randomly distributed throughout the U3 Unit. Some of the Cr-rich zones have corresponding high PGE values, but just as many do not have any high PGE values. The overall distribution of PGEs is just as random as Cr. Rock types that host high PGE values are varied and include: massive oxide; oxide and/or sulfide-bearing ultramafic layers; sulfide-bearing troctolitic rocks; and sulfide-bearing pegmatitic zones. However, there are just as many zones of these varied rock types that are ‘barren’ of high PGE values. Clearly, both PGEs and Cr are randomly distributed within the U3 Unit. The presence of Cl-rich drops on the drill core indicates that rocks of the U3 Unit are Cl-enriched, and thus were probably subjected to invasion by Cl-bearing hydrothermal solutions. These solutions could have potentially carried and introduced PGEs into the U3. They also could have remobilized and redistributed PGEs that were initially present within the U3.

RELATIONSHIP BETWEEN PGEs, CHROMIUM, AND COPPER

The importance of a chromium association to PGEs was stressed when only the occurrences in drill hole Du-15 were known (Sabelin and Iwasaki, 1986; Sabelin, 1987). However, recently drilled holes in the BLD, and additional analytical data collected since 1986, indicate that this association is not always valid - high Cr values and high Pt+Pd values are not always correlative, especially on a 1:1 basis.
Figure 52 illustrates that high Cr and high Pd values from the U3 and PEG units are not always correlative. In fact, some of the samples that contain high Pd values contain extremely low Cr values. Even on an individual drill hole basis, a Cr to PGE association is not fully indicated. For example, drill hole BL-90-3 contains several Cr-rich zones (up to 2,654 ppm), but the drill hole contains no significantly mineralized PGE intervals. These data suggest that zones of high Cr content may have been only locally important in scavenging PGEs (as in Du-15).

Because Cr appears to have been at least locally important in concentrating PGEs, a review of all the analyses of rocks within, and footwall to, the SKI was conducted. This review indicates that Cr values of 300-400 ppm are not uncommon within the U1, U2, U3, BAN, BIF inclusions, and VIRG Sill units. In addition, chromium values in excess of 1,000 ppm are associated with the U2, U3, BAN, and VIRG Sill. Furthermore, the U2, U3, and BAN units only contain Cr values in excess of 1,000 ppm when they contain massive oxide horizons; the highest values of this group are associated with the U3 Unit (up to 7.72% Cr₂O₃). The high Cr values are generally associated with some massive oxide horizons, and to a lesser extent with some ultramafic and troctolitic layers. However, there is no relative consistency as to which rock type is Cr-rich (even within a single drill hole). Collectively, the data from all the analyses indicate that the bottom most units of the SKTS (U2, U3, and BAN) are Cr-rich only when massive oxides are present. As mentioned earlier, the massive oxides appear to be empirically related to intruded and assimilated BIF that was capable of generating an oxide-
rich 'restite.' In turn, this 'restite' must have acted as a trap that was capable of concentrating Cr (as well as Ti) from the magma. This is supported by high Cr values (400-900 ppm) associated with recognizable BIF inclusions (see SOKSORT.WK1 and SOKAWR.WK1). Another potential source of the high Cr within the bottom SKTS unit is the VIRG Sill - it contains values that range from 800 to 2,327 ppm Cr (Severson, 1991). In addition, some of the sills within the BIF are found to contain high Cr values (Hauck, in prep.). One hypothesis currently being investigated (Hauck, in prep.) is that the high Cr contents of the U3 are related to Cr-rich sills within the BIF.

The importance of a Cu depletion to high PGEs was also stressed when only the Du-15 occurrence was known (Sabelin and Iwasaki, 1986; Sabelin, 1987). Again, recently drilled holes and acquired analytical data indicate that this association is not always valid. Figure 53 is a plot of Pd versus Cu for all analytical data from the U3 and PEG units. This plot illustrates that high Pd values (>1,000 ppb) are associated with both high and low Cu values that range from <100 ppm to 8,000 ppm. However, it is interesting to note that samples with more than 8,000 ppm Cu rarely contain greater than 2,000 ppb Pd. Overall, the data suggest that a high Cu content (<8,000 ppm) may also be locally important relative to high PGE content. The presence of secondary sulfides within the U3 Unit indicates that some redistribution of the sulfides has occurred after, or during, a serpentinization event (see above discussion). Introduction of the PGEs within the U3 Unit may have occurred during this remobilization event.

Figure 53. Pd versus Cu for samples collected from the U3 and PEG units.
Figure 54 illustrates that most of the high PGE values from the U3 and PEG units exhibit a Pt:Pd ratio that varies from 1:1 to 1:3.

**Figure 54.** Pd versus Pt for samples collected from the U3 and PEG units.

**ORIGIN OF PGEs WITHIN THE U3 UNIT**

Boudreau and McCallum (1992) recently propose a model pertaining to the formation of Pt-Pd reefs within the Stillwater Complex. The model suggests that the J-M reef was formed "...by exsolution of Cl- and volatile-rich fluids from footwall intercumulus liquids which leached and transported ore components (both PGE and S) upward to the level of the reef....Zones of PGE and S enrichment can occur where degassing fronts encounter stratigraphic physical-chemical discontinuities..." (Boudreau and McCallum, 1992, p. 1830). The authors highlight the importance of chlorine in the transport of the PGE. Late magmatic, chlorine-rich fluids have also been envisioned as an important PGE concentrator within the Duluth Complex (Morton and Ameel,
Chlorine-rich drops are found in numerous zones throughout the PRI and SKI. Their distribution strongly suggests that Cl-rich solutions have migrated upward through both intrusions. Chlorine-rich drops are also found in the top portions of the BIF. Their presence in footwall rocks suggest that Cl-rich solutions may have either: migrated laterally out of the SKI into the adjacent footwall rocks; or migrated upward through the footwall rocks from a deep-seated source in the Keweenawan Midcontinent Rift. Ripley et al. (1993) suggest that the fluids are a combination of fractionated magmatic fluids and fluids derived from external metasedimentary country rocks.

The model of Boudreau and McCallum (1992) seems to reasonably explain why anomalous PGE values (>100 ppb Pd, >50 ppb Pt) are so common to the U3 Unit of the SKI. According to the model as applied to the Duluth Complex, an upward-moving, high-temperature, Cl-rich, intrusion-wide hydrothermal front was capable of remobilizing minor amounts of PGEs and S in the lower sulfide-bearing part of the SKTS (BAN and BH Units). The hydrothermal solution became progressively enriched in PGEs and sulfides as it migrated upward in the cumulus pile. Eventually, it encountered a stratigraphic trap and deposited the PGE and sulfides. Within the SKTS the U3 Unit represents the lowest stratigraphic trap that upward-moving Cl-rich solutions would have encountered first. The U3 contained both sulfides and Cr-bearing minerals that could have acted as local reductants that initiated PGE precipitation from the Cl-rich solution. The presence of Cl-rich rocks (and the resultant Cl-drops) attests to the fact that Cl-rich solutions have migrated through the U3 Unit. It is possible that the Cl-rich front continued to move upward beyond the U3 Unit, as suggested by the presence of Cl-rich rocks in the U1 and U2 units, but the front became
depleted in PGEs when it encountered the U3 Unit (the U1 and U2 units do not contain appreciable amounts of PGEs).

There are two problems to this model. First, the units beneath the U3 do not have sufficient thickness and/or primary PGE concentration from which appreciable amounts of PGE could have been leached. In this regard, the model was only capable of producing ‘anomalous PGEs’ in the U3 that never quite reached ore-grade. Second, the model does not predict why significantly higher PGE values are restricted to smaller areas within the SKI if an intrusion-wide front is envisioned. Rather, specific drill holes in the SKI contain high PGE values while other drill holes are void of high values even though the geologic setting of all these holes is the same. For example, the following drill holes contain little or no high PGE values even though the U3 Unit contained massive oxide pods and high Cr values: BL-68, Du-12, Du-14, Du-16, 34872, C-88-1, and BL-90-3. On the other hand, high PGE values are restricted to a small group of holes where the same geologic conditions are present (massive oxide pods with high Cr values) and include: Du-9, Du-15, BL-89-1, BL-89-2, and BL-90-1. Both of the above listed problems suggest that an intrusion-wide front was not entirely responsible for the elevated PGEs in the Birch Lake deposit area. In essence, a straightforward application of the ‘Boudreau-McCallum model’ may be incorrect. However, these problems also suggest that specialized local conditions may have been operational within the confines of the model. A possible explanation why the restricted group of drill holes at the BLD contains significant PGEs is that the BLD represents an area where there was a local increase in the amount of upward-moving Cl-rich solutions. Upward-moving solutions could have been concentrated, or funneled, within vertical fault zones that were active during and after emplacement of the SKI.
Several geologic oddities can be utilized to define linear zones that may reflect fault zones where upward-moving and PGE-pregnant, Cl-rich solutions could have been concentrated. These oddities are listed below:

1. Drill holes with significant PGE values can be used to outline linear zones. However, this outlines only the BLD area and cannot be used to predict where other significantly PGE-mineralized zones may occur. A problem with this concept is that the deep portions of several pre-1980 drill holes are quarter-cored, and thus, cannot be sampled for PGE analysis according to MDNR guidelines - this effectively limits the areal extent of where the U3 Unit can be sampled.

2. Drill holes that intersect sulfide mineralization within the granitic footwall rocks outline linear zones that appear to be related to faults. (previously discussed in the Regional Geology section, p. 17-20). They outline two northeast-trending belts shown on Figure 55-A (replotted from Fig. 4). The southernmost belt is informally referred to as the Birch Lake Fault. Several lines of evidence suggest that these belts were formed within the footwall rocks while the basal portion of the SKI was intruded (see Regional Geology section). Footwall massive sulfide veins are common within these belts and were probably formed by downward expulsion of an basal immiscible sulfide melt into faulted and fractured footwall rocks. The footwall veins are Cu-enriched, relative to massive sulfides in the overlying SKI, as a result of fractional crystallization of the sulfide melt as it moved down through the footwall rocks. A similar mechanism of Cu-enrichment, and PGE-enrichment, is envisioned for footwall sulfide veins at the Strathcona Mine of the Sudbury Intrusion (Naldrett et al., 1992). However, the sulfide veins below the SKI are not particularly PGE-enriched.

3. Drill holes that intersect thick sequences of late granitic/felsic lenses may also be instrumental in defining fault zones that were active during and after emplacement of the SKI. Because these lenses are near vertical and may be randomly intersected in a drill hole, it is difficult to quantify which group of holes cut ‘voluminous’ amounts (increased amounts and/or common amounts) of granitic lenses. With this caution in mind, a review of the cross-sections that accompany this report indicates that fairly ‘voluminous’ amounts of
granitic lenses are common within the following drill holes: BI-68; 40910; 40906; D-6A; D-9; E-5; DU-10; BL-90-2; DU-14; 32718; DU-19; and DU-20. (Note that the hybrid/metasomatic replacement zones of BL-90-2 are also included in the granitic category; see p. 164). Most of these drill holes outline a narrow northeast-trending belt (Fig. 55-B) where late granitic lenses are commonly encountered. This belt is informally referred to as the Birch Lake Fault.
Figure 55-A. Distribution of sulfide mineralization within the footwall Giants Range Batholith (see also Figure 4).

Figure 63-B. Distribution of 'voluminous' late granitic/felsic lenses (gr) that cut SKTS units.
In comparing the belts in Figures 55-A and 55-B, the granitic belt coincides exactly with the belts of footwall sulfide mineralization. The overlap of both belts suggests that northeast-trending faults were an important control on subsequent fluid activity. Furthermore, because early-formed footwall mineralization is superimposed on late-formed granitic lenses, it appears that the fault zones were active throughout the intrusive history of the SKI. This fault longevity suggests that some northeast-trending fault zones may have continuously provided channelways that could have subsequently concentrated Cl-rich hydrothermal solutions. Increased fluid flow of Cl-rich upward-moving solutions could have carried significantly more PGE upward to the U3 stratigraphic trap. Interestingly, the belts that delineate the Birch Lake Fault (Fig. 55-A and 55-B) trend through the BLD area where significant PGE mineralization has been encountered in the U3 Unit. Drill holes that do not contain significant PGE associated with the U3 Unit are positioned outside of the Birch Lake Fault.

In summary, the coincidence of sulfide-mineralized granitic footwall rocks, late cross-cutting granitic lenses, and the PGE-enriched BLD area, suggest that upward-moving, Cl-rich hydrothermal fluids could have been more concentrated in fault zones, e.g., the Birch Lake Fault. Wherever increased fluid flow encountered a stratigraphic trap, PGEs were deposited. Thus, the BLD is unique in that it is situated in an area where these features intersect. A hypothetical sketch of the ‘Boudreau-McCallum model’ as applied to the SKI is portrayed in Figure 56. Whether a significant PGE deposit is present in the SKI is dependant on a combination of: 1) the volume of lower SKTS units from which potential PGEs were leached by upward- and laterally-moving Cl-rich solutions; 2) the volume of fractured material (channelways) within and adjacent to the faults; 3) continued reactivation of the fault that repeatedly established available channelways; 4) the volume of Cl-rich fluids that were channeled into the faulted and fractured zones; and 5) the amount of reductant phases (sulfides, massive oxide pods, and/or high Cr contents) that were
initially present within the U3 Unit. All of these conditions have certainly been met within localized areas of the SKI, but more detailed drilling along these northeast-trending belts is necessary to determine if a significant PGE deposit is present.

Figure 56. Schematic diagram showing the possible role that fault zones may have played in funneling upward-moving, Cl-rich solutions and the resultant deposition of significant PGEs within the U3 unit of the Birch Lake area.
SUMMARY AND CONCLUSIONS

SUMMARY OF THE SOUTH KAWISHIWI TROCTOLITE SERIES (SKTS)

Detailed relogging of ‘hundreds-of-thousands’ of feet of drill core has defined an igneous stratigraphic section within the SKI. However, it must be stressed repeatedly that the SKTS section is not consistent throughout the SKI. At least 17 correlative igneous units are identified, but they are not equally present in all areas. There are innumerable lateral and down dip changes within the SKI that are manifested by: 1) pinch-outs of certain units - sometimes this is accompanied by the reappearance of the unit elsewhere at the same stratigraphic position (this is especially true of the U1, U2, and U3 units); 2) drastic thickness variations associated with a particular unit (this is especially true of the BH Unit); 3) changes in the stratigraphic position of a particular unit relative to other units of the SKTS (this is only true of the U3 Unit - it may be present in either the BH or BAN units); 4) down-strike gradational changes in modal percentages of minerals associated with a particular unit - as a result, the dominant rock type of a particular unit may become less voluminous elsewhere in the stratigraphic section (this is especially true of the MAIN AGT Unit); and 5) very thick exotic rock packages (such as the HIC which represents a large inclusion) are scattered throughout the SKI and make drill hole correlations to ‘normal’ SKTS rock packages difficult. In some cases, these changes are an artifact of the classification system used in this investigation. For example, the SKTS units are classed according to the dominant rock type, and/or rock packages, that can be correlated between drill holes. This does not imply that each of the igneous units represents an individual cooling unit or event. Nor does it completely take into account changes that are related to contamination of the original melt due to assimilation of footwall rocks. Because of these difficulties, it is not surprising that many of the defined igneous units portray lateral gradational changes. However, in spite of these difficulties, a gross
stratigraphy of at least 17 recognizable igneous units is established for the SKI. The configuration and stacking arrangement of these units is illustrated in Figure 10. The major characteristics of each of the units of the SKTS are summarized in Table 3.

The lowest units of the SKTS are the BAN, BH, PEG, U1, U2, and U3 units. All units are sulfide-bearing. These units are the most variable of all rock packages within the SKI with respect to unit thickness changes, homogeneous versus heterogeneous textured rock packages, sulfide content, and limited spatial extent. These variations are summarized below:

1. The lower SKTS units exhibit an overall heterogeneous nature. For example, if the U1 Unit is present in a particular area, then the rocks directly below it are generally heterogeneous-textured and sulfide-bearing. In the absence of U1, the rocks below the PEG Unit are sulfide-bearing and heterogeneous. However, the PEG Unit is not present throughout the

### Table 3. Summary of distinguishing characteristics pertinent to the various igneous units of the South Kawishwi Troctolite Series (SKTS).

<table>
<thead>
<tr>
<th>UNIT</th>
<th>MAJOR ROCK TYPE</th>
<th>THICKNESS (ft) (range)</th>
<th>PLAG SYMP</th>
<th>JLM/MGT COMPOSITE</th>
<th>JLM/Ti+Cr COMPOSITE</th>
<th>MISCELLANEOUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT (T)</td>
<td>Anorthite, Tract.</td>
<td>1,200</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AT &amp; T</td>
<td>An. Tract &amp; Tract.</td>
<td>(1,200-2000)</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UW</td>
<td>Sulf-brg Tract.</td>
<td>(100-900) wedge-like</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>two ultramafic zones (UW1 &amp; UW2)</td>
</tr>
<tr>
<td>MAIN AGT</td>
<td>Augite Tractolaite</td>
<td>900 (270-1,380)</td>
<td>✓/✓</td>
<td>✓</td>
<td></td>
<td>hybrid rocks common near base at Dunka Pit area</td>
</tr>
<tr>
<td>U1</td>
<td>55% ultramafics 45% trachytes</td>
<td>110 (5-130)</td>
<td>Rare</td>
<td>JL dominant</td>
<td>✓</td>
<td>uppermost sulfide-bearing unit at Dunka Pit and Spruce Road</td>
</tr>
<tr>
<td>BH</td>
<td>Sulf-brg Heterog. Tractolaite</td>
<td>90-1,700</td>
<td>Rare</td>
<td>Jl dominant</td>
<td></td>
<td>Highly variable thickness !</td>
</tr>
<tr>
<td>AT-T</td>
<td>An. Tract to Tract.</td>
<td>900 (70-1,200)</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>locally sulfide-bearing at Dunka Pit area</td>
</tr>
<tr>
<td>U2</td>
<td>36% ultramafics 64% trachytes</td>
<td>90 (5-425)</td>
<td>Rare</td>
<td>Jl dominant</td>
<td>✓</td>
<td>sulfide-bearing at Dunka Pit and Spruce Road, mass ox in BJ-68</td>
</tr>
<tr>
<td>PEG</td>
<td>Tract with common pegmatitic zones</td>
<td>95 (10-260)</td>
<td>✓</td>
<td>Jl dominant</td>
<td>✓</td>
<td>locally sulfide-bearing</td>
</tr>
<tr>
<td>U3</td>
<td>33% ultramafics 67% trachytes</td>
<td>100 (3-410)</td>
<td>Rare</td>
<td>Jl in dominant in mass oxides</td>
<td>✓</td>
<td>PGE-bearing zone; massive oxides and B11 incl's common green pleonaste common.</td>
</tr>
<tr>
<td>BAN</td>
<td>Augite Tract (top) Noite (bottom)</td>
<td>125 (10-380)</td>
<td>Rare</td>
<td>Jl dominant</td>
<td></td>
<td>sulfide-bearing; contains most mass sulfs, occurrences mass ox and B11 incl's at Dunka Pit</td>
</tr>
<tr>
<td>T-AGT</td>
<td>Tract &amp; Aug. Tract.</td>
<td>70-450</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UPPER PEG</td>
<td>Pegmatoidal Tract.</td>
<td>77-139</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JINCL</td>
<td>Gravel “Ox Gab”</td>
<td>(300-540)</td>
<td></td>
<td></td>
<td></td>
<td>sheet-like CC Inclusion (basalt?)</td>
</tr>
<tr>
<td>UPPER GABBRO</td>
<td>Gabro</td>
<td>(20-855)</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AN-G GROUP</td>
<td>49-79% Anorthite</td>
<td>1.850 (1,600-2,450)</td>
<td>✓</td>
<td>Jl in dominant</td>
<td></td>
<td>contains semi-nass graphite veins</td>
</tr>
</tbody>
</table>

180
SKI, and in its absence the rocks of the U3 Unit mark the top of sulfide-bearing rocks of the SKTS. Another example is the down dip change in character of the BH Unit into the AT-T Unit. At Dunka Pit, the BH Unit is defined by heterogeneous sulfide-bearing rocks; however, it gradually becomes homogeneous and sulfide-barren toward the Birch Lake deposit. Eventually, the BH Unit becomes indistinguishable from, and merges into, the AT-T Unit, which is present at the same stratigraphic level at the Birch Lake deposit. The abrupt up-dip disappearance of the U1, U2, and U3 units in the Dunka Pit area is another example. Finally, the BH Unit exhibits drastic thickness changes. All of these variations suggest that a complicated intrusive history best describes the lower portion of the SKTS.

2. The lower SKTS units record the effects of contamination to the magma from intruded and assimilated country rock. Rocks of the SKTS that show the most profound effects of contamination are the BAN and U3 units. Both units often contain massive oxide horizons that are situated in close proximity to either BIF inclusions and/or BIF footwall rocks. This empirical relationship suggests that the massive oxides are related to intruded and assimilated BIF. In addition, the basal portion of the BAN Unit contains noritic rocks that are related to contamination from the underlying GRAN. The effects of contamination in the BAN Unit are also illustrated by its position in the whole rock X-Y plots of this report. The BAN Unit generally plots in a separate field that shows some overlap with the other lower SKTS units. Additional effects of contamination are recorded in the BH Unit. Its heterogeneous texture and sulfide-content are probably related to devolatization and assimilation of the Virginia Formation.

3. The ultramafic-bearing units (U1, U2, and U3) record repetitive magmatic injection events. Each of these units are characterized by subhorizontal olivine-rich layers (picrite, peridotite, etc.) that repeatedly alternate with troctolitic layers. Gradational tops and sharp bases are commonly present within the ultramafic layers and indicate that crystal settling may have been important in their development. These features indicate the ultramafic-bearing units represent periods of rapid and continuous magma injection that crystallized more primitive ultramafic layers before mixing with the resident magma. However, the U1, U2, and U3 units each contain a highly variable number of individual ultramafic layers (even between close-spaced drill holes!) that is not fully understood. For example, up to 20 individual
ultramafic layers are present within a drill hole where it encountered the U1 Unit; whereas in a nearby drill hole, only one ultramafic layer defines the U1 Unit. This suggests that local magmatic conditions may have also been responsible and dictated the number of ultramafic layers that crystallized in a particular area. These localized conditions could have been related to either magmatic density currents and/or variations in the topography at the top of the cumulus crystal pile.

4. Many of the SKTS units exhibit lateral changes and pinch-outs that suggest that the bottom of the SKI is compartmentalized. For example, any of the ultramafic-bearing units (U1, U2, and U3) may be totally absent in one area and then reappear down strike at the same stratigraphic level. Also, the PEG Unit can only be recognized in the Birch Lake and Maturi areas, but it is apparently lacking in the Dunka Pit and Spruce Road areas. Finally, thick sequences of the BH Unit are present at the southwestern and northeastern portions of the SKI (Dunka Pit and Spruce Road deposits, respectively), but the BH Unit thins drastically in the intervening area. This compartmentalized nature may indicate that the lower portion of the SKI was emplaced into several restricted small magma chambers.

All of the above features suggest that the lower portion of the SKI was emplaced as a series of repeated and rapid influxes of new magma into several restricted chambers that eventually coalesced with continued magmatic injection to produce the overall heterogeneous and compartmentalized nature of the lower SKTS. This intrusive history was further complicated by the effects of contamination to the magma from assimilated country rocks. Localized conditions (density currents and floor topography) within each of the restricted chambers further complicated the intrusive history. It appears that the conditions of such a complicated history would have been most prevalent during the earliest stages of SKI emplacement.

The UW Unit may have also originated in the same manner. It is a texturally heterogeneous, sulfide-bearing, and inclusion-bearing unit that is positioned at the same stratigraphic level as the texturally homogeneous and sulfide-free MAIN AGT Unit. Spider diagram profiles for these two
units are different. The differences between these two units, now at the same stratigraphic level, could be the result of an earlier UW Unit that was emplaced in a restricted chamber and was later cut off down dip by the MAIN AGT Unit. A similar explanation of earlier intrusions that are cut off down dip has been suggested by Martineau (1989). However, this situation appears to be only applicable to the UW Unit of the SKTS, which is restricted to the Dunka Pit area.

In contrast, the upper units of the SKTS reflect an entirely different intrusive history. These units include the MAIN AGT, LOW AGT, AT-T, AT&T and AT(T). Each unit is characterized by a monotonous sequence of texturally homogeneous and sulfide-free rocks. Gradational contacts are present between each of the units. Ultramafic members are restricted to only two thin horizons (High Picrite #1 and #2). These features are indicative of a quiescent and open magmatic system characterized by more static conditions. Quiescent conditions would have been more prevalent during the later stages of SKI emplacement due to a progressively developed large magma chamber.

In summary, the lower units of the SKTS were emplaced early into several restricted magma chambers via repeated and close-spaced magmatic pulses. The effects of contamination from assimilated and devolatized country rocks were most pronounced during this event. The upper more homogeneous-textured units of the SKTS were emplaced into a progressively developed open magma chamber with little interaction with the country rocks.

**SUMMARY OF THE HIGHWAY 1 CORRIDOR**

An entirely different package of rocks is present in six extremely deep holes drilled within the Highway 1 Corridor (H1C). This package is surrounded by drill holes that intersect 'more typical' SKTS rocks, and thus, the H1C may represent a large inclusion. Because anorthositic rocks are common within the H1C, it may be related to Anorthositic Series rocks that are mapped within 3-4 miles to the southeast by Green et al. (1966). The H1C is capped, and bottomed, by SKTS rocks
that are correlative with outlying drill holes. This suggests that the HIC is an exotic package of rocks, albeit a very thick package, that is totally surrounded by SKTS-type rocks. All of these features suggest that the HIC is a large inclusion of Anorthositic Series rocks that is completely isolated within the SKI. The age of the rocks within the HIC should, therefore, be considerably older than the SKI, but no age dates are available for either the Anorthositic Series and SKI rocks in this vicinity.

At least five correlative units are present within the HIC and include (from top to bottom): T-AGT; UPPER PEG; ‘INCL’; UPPER GABBRO; and AN-G GROUP. The UPPER GABBRO and AN-G GROUP comprise the majority of the HIC package. These units consist of alternating anorthositic and gabbroic rocks. Semi-massive graphite veins are intersected within the AN-G GROUP in four drill holes. The ‘INCL’ is present as a 300-500 foot thick sheet that dips at 11E-15E to the south. It is characterized by a fine-grained granular oxide gabbro rock that locally contains vesicles. Because of its high magnetite content, the ‘INCL’ is different than ‘typical’ basalt inclusions that have been correlated with the North Shore Volcanic Group. The ‘INCL’ appears to be similar to the Colvin Creek (CC) type inclusions of Severson and Hauck (1990) and Severson (1991).

Whole rock X-Y plots and spider diagram profiles of the HIC rocks indicate the following: 1) all internal units of the HIC are dissimilar, except for the T-AGT Unit and AN-G GROUP (gabbroic rocks); 2) all internal units of the HIC are dissimilar when compared to all of the SKTS units; and 3) the ‘INCL’ does not compare well with either basalt or CC inclusions. The lack of chemical comparison between the HIC and SKTS rocks confirms that the HIC is an exotic rock package within the SKTS.

The existence of a large inclusion of Anorthositic Series rocks, presumably older, within the SKI is interesting. Because ‘typical’ SKTS rock types occur below the HIC (see Fig. 10), it appears
that an older intrusion of the Duluth Complex could be underplated by a younger intrusion. This concept could also be extended to the north into the Omaday Lake area (section 30, T.62N., R.10W.) where a steeply-inclined inclusion of BIF is contained within a package of anorthositic rocks (see Plate I-A; from Green et al., 1966). Within the SKI, inclusions of BIF are subhorizontal and generally occur very close to the basal contact. However, the Omaday Lake BIF inclusion crops out in an area that is 1.5 miles from where the basal contact is exposed (toward the interior of the Complex). This means that the Omaday Lake BIF inclusion is roughly positioned 2,500-3,500 feet above the basal contact! A possible explanation of this phenomenon may be that the Omaday Lake BIF inclusion is contained within Anorthositic Series rocks that were later underplated by the SKI. Thus, all of the anorthositic rocks within R.10W. of Plate I-A may be correlative with Anorthositic Series rocks. In this report, anorthositic rocks in R.10W. (agu and ago map units in Plate I-A) are tentatively separated from the SKI by a northeast-trending fault. Several drill holes are present within R.10W., but only four of them are preserved intact. A quick review of the drill core reveals that these holes did not intersect any identifiable SKTS rock packages.

The MAIN AGT Unit has only been encountered in drill holes to the southwest of the HIC (see Fig. 10). A complete absence of the MAIN AGT Unit is obvious within the Spruce Road area. However, the uppermost SKTS units (AT&T, etc.) are present on both sides of the HIC. These relationships signify that large inclusions within the SKI can have a profound affect on magma chamber development. In essence, the MAIN AGT did not crystallize to the north of the HIC because the HIC acted as an ‘obstruction.”

**SUMMARY OF PRTS UNITS**

Several drill holes within the PRI are relogged to better understand the nature, and location, of the contact between the PRI and SKI. One important feature noted in this investigation is that
as the contact between the two intrusions is approached, the upper PRTS units become heterogeneous and indistinguishable from each other. A similar heterogeneous nature is not evident in the adjacent SKTS. A second important feature noted is that voluminous amounts of late cross-cutting granitic/felsic and pyroxenitic rocks are intersected in drill holes that are situated to the immediate west of a north-trending fault zone (referred to as the Grano Fault). Finally, a new unit referred to as the Basal Ultramafic Unit (BU Unit) is added to the PRTS. It is present at the basal contact within the vicinity of the Grano Fault wherever the BIF is in direct contact with the Complex. The BU Unit consists of an upper picrite-peridotite zone (± massive oxides) that grades down into a lower orthopyroxenite zone. The lower zone in turn grades down into the BIF and in some instances the contact between the two is arbitrarily chosen. These relationships indicate that contamination of the magma from assimilated BIF was important in forming the BU Unit. Also supporting this concept are the similar spider diagram profiles for both the BU and BIF units.

**SUMMARY OF THE SKTS VERSUS PRTS UNITS**

Two entirely different stratigraphic packages are present within the SKI and PRI. Major differences between the two are listed in Table 4.
Table 4. Summary of distinguishing characteristics pertinent to the South Kawishiwi intrusion versus the Partridge River intrusion.

<table>
<thead>
<tr>
<th>SKTS</th>
<th>PRTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Augite trクト common in upper half (MAIN AGT) and very bottom (BAN)</td>
<td>Augite trクト common in lower half (Unit I) and minor portions of upper half (Unit IV)</td>
</tr>
<tr>
<td>Ultramafic layers present as packages in lower half (U1, U2 &amp; U3)</td>
<td>Ultramafic layers not common in lower half (discont. layers in Unit I)</td>
</tr>
<tr>
<td>Ultramafic layers rarely present in upper half (High Picrite #1 &amp; #2)</td>
<td>Ultramafic layers common in upper half (base of Units IV, VI and VII)</td>
</tr>
<tr>
<td>Virginia Fm. inclusions not very common in lower half (BH &amp; UW)</td>
<td>Virginia Fm. inclusions very common in lower half (Unit I)</td>
</tr>
<tr>
<td>BIF inclusions common in U3 and BAN</td>
<td>No BIF inclusions: BU Unit present where BIF is in direct contact w/ Complex</td>
</tr>
<tr>
<td>Plag. symplectite common in upper half (PEG, UW, MAIN AGT, AT-T, AT&amp;T, and AT(T))</td>
<td>Plag. symplectite common in lower half (Unit I)</td>
</tr>
<tr>
<td>Intercumulus Opx content is higher (2-3%) in all rock units (thick Opx rims around olivine)</td>
<td>Intercumulus Opx content is lower (&lt;1%) in all rock units (thin Opx rims around olivine)</td>
</tr>
<tr>
<td>Inverted pigeonite is present in all units</td>
<td>Inverted pigeonite is rare to all units</td>
</tr>
</tbody>
</table>

**SUMMARY OF THE OUI AND gr UNITS**

In most instances, increased amounts of late cross-cutting OUIs and granitic/felsic rocks (gr) are associated with structural discontinuities or faults. A perfect example of this is the north-trending Grano Fault, which was so named because it contains abundant OUI and gr lenses that are common in an area immediately west of the fault. In many cases, both OUI and gr lenses alternate within a single drill hole that was put down in the vicinity of the Grano Fault. Another zone where late granitic lenses are common is in a northeast-trending zone that trends through the Birch Lake deposit (see Fig. 55-B).

Geochemical sampling of the OUIs and granitic rocks reveals a wide variation in chemistry. The granitic rocks are similar to granitic rocks present in the Giants Range Batholith. The OUIs
can be grouped into two categories: oxide-rich (15%) and oxide-poor. The two different OUI groups suggest that they originated: 1) via different modes of genesis; 2) during different events; or 3) under different geochemical conditions. Unfortunately detailed geochemistry on the varieties of OUIs is lacking to sufficiently address these differences.

Within the PRI, OUIs are found in two different areas where the BIF is present at the basal contact. These two areas are: 1) the Longnose-Longear-Section 17 area (Severson and Hauck, 1990); and 2) the Grano Fault area (this includes the late OUI lenses and, possibly, the similar-looking BU Unit at the basal contact). Overall, these spacial relationships suggest a genetic link of OUIs to areas where massive iron-formation assimilation occurred at the basal contact. In this manner, partial melts derived from assimilated iron-formation may have been emplaced into structurally prepared zones and formed the OUIs. The partial melts that formed the OUIs were enriched in titanium via a metasomatic transfer mechanism. Some enrichment in titanium is documented for portions of the BIF in direct contact with the Complex, and Muhich (1993a, 1993b) proposes a metasomatic transfer mechanism. Whether this process can account for the extremely high Ti concentrations in the OUIs has yet to be demonstrated. The OUIs could also have originated by a metasomatic replacement mechanism as is proposed for iron-rich plugs in the Bushveld Complex (Schiffries, 1982; Viljoen and Scoon, 1985).

SUMMARY OF STRUCTURAL FEATURES

Several fault zones have been delineated in this study. Some of the faults exhibit a 'scissors-type' movement, in that the relative motion on the fault decreases away from the Duluth Complex. 'Scissors-type' faults have also been recognized within the Peter Mitchell Mine (Severson, in prep.). These observations suggest that movement on the faults were initiated during emplacement of the Duluth Complex. Most of the faults offset both footwall and Complex rocks, indicating that
movement along the faults continued after emplacement of the Complex. A brief summary of the more unique faults is presented below:

**Grano Fault**

The Grano Fault is a major north-trending fault situated about at the boundary between the SKI and PRI. The fault exhibits a relative motion of down to the east. At its southern end, the fault exhibits the most motion (100-250 feet), but the amount of discernable motion diminishes to the north (away from the interior of the Complex). In the Serpentine deposit, the fault is responsible for fracturing the BIF before/during emplacement of the BIF Sill and VIRG Sill. As a result, one of these sills bifurcated into BIF submembers A and B in the vicinity of the Grano Fault to form the EXTRA BIF Sills. Because the sills are metamorphosed by the Complex, initiation of movement along the Grano Fault is inferred to be early-Complex (Logan sill age?). The presence of granitic/felsic and OUI lenses that cross-cut troctolitic rocks in the vicinity of the fault zone suggest that the Grano Fault was also reactivated after emplacement of the PRI. Because these late lenses do not persist along the fault trend to the north into the SKI, the PRI is inferred to be older than the SKI.

**Fault B-29**

Fault B-29 is a north-trending fault, down to the east, in the northern Dunka Pit area. At its northern extremity, the fault juxtaposes BIF, west of the fault, against SKI rocks to the east of the fault. Movement along the fault appears to have been initiated before emplacement of the SKI. Initially, BIF and Virginia Formation were juxtaposed across the fault. A pre-SKI age is suggested by several lines of evidence; the major evidence is a BIF character change and chemical change within the fault zone (Ti enrichment of the BIF due to the metasomatic transfer of Ti across the
fault/contact). Fault B-29 is traced further to the south in this investigation where several horsetail splays are indicated by offset units in drill hole. The overall amount of motion associated with Fault B-29 gradually increases toward the south (toward the Complex). This suggests that Fault B-29 is a 'scissors-type' fault.

**Birch Lake Fault**

The inferred presence of the Birch Lake Fault is defined by a zone wherein drill holes commonly encounter either: massive sulfide mineralization within the footwall rocks; and/or increased amounts of late granitoidal lenses that cut the troctolitic rocks of the SKI. Interestingly, this fault trends through the Birch Lake Deposit where significant PGEs are associated with the U3 Unit. Evidence pertaining to the amount of offset associated with this fault are meager. On Plate XIII, offset footwall and SKTS units are apparent between drill holes KA-3 and Du-17 (note that the actual fault trace is, unfortunately, not drawn on this cross-section). The indicated sense of motion on the Birch Lake Fault in Plate XIII is about 200-300 feet, down to the east. This fault represents a true half-graben fault in that not all of the SKTS section are offset across the fault (note that the 'High Picrite #1,' and other upper SKTS units, are apparently continuous across the fault).

**Unnamed Faults**

A northeast-trending fault is inferred to separate "Anorthositic Series" rocks (in Range 10 West on Plate I-A) from 'typical' SKTS rocks intersected in drill hole to the west of the fault. This fault is proposed to explain why the Omaday BIF inclusion, within 'Anorthositic Series' rocks, is positioned too high above the basal contact. It appears that the 'Anorthositic Series' rocks in R.10W. may have been underplated by the SKI.
Two potential faults are suggested by offset SKTS units on two of the cross-sections (unfortunately the faults are not shown on the cross-sections and must be described verbally). On Plate VI-B, the offset nature of the MAIN AGT Unit (down to the east) in drill holes DR-2 and D-6A is probably related to a fault (Birch Lake Fault?). Substantial offset of footwall rocks is apparent between drill holes 34870A and 34872 in Plate XIV. These two holes are only 1,200 feet apart, yet the basal contact is displaced by over 1,250 feet (down to the northeast).

**NATURE OF THE PRI-SKI CONTACT**

The presence of dissimilar stratigraphic packages in the PRI and SKI suggests that both intrusions represent separate emplacement events. This in turn, suggests a relative age difference between the two intrusions. The unique occurrence of the ‘heterogeneous zone’ at the margin of the PRI, but not in the adjacent SKI, may indicate that the PRI is older than the SKI. The ‘heterogeneous zone’ is envisioned to have formed as a rind along the outermost margins of the PRI magma chamber wherever country rocks were intruded and assimilated. Contamination of the magma is, therefore, more pronounced in these areas, and as a result, the upper units of the PRTS are more heterogeneous and thus, indistinguishable from each other. In this manner, the ‘heterogeneous zone’ marks the outermost edge of the PRI chamber where the upper units were once in contact with the country rocks. The country rocks are no longer preserved to the east of the ‘heterogeneous zone’ because they may have been effectively removed by the SKI which was later emplaced against the PRI. However, a ‘curtain’ of country rocks still separates the PRI and SKI in select areas, such as, north of the Babbitt deposit in section 29 (T.60N., R.12W.). Additional data also suggest that the PRI is older than the SKI. One example is that late granitic/felsic and OUI lenses associated with the Grano Fault are present in only the PRI even though the fault trends
through both intrusions. This suggests that only the PRI was present prior to the event that produced the late granitic lenses.

SUMMARY OF FOOTWALL ROCKS

Several unique features are associated with the footwall rocks and are briefly summarized. Wherever the Giants Range Batholith is footwall to the Complex, a discontinuous zone of K-spar and quartz depleted granitic rock is present within the upper 0-210 feet. This zone is referred to as the "contaminated" zone, or 'cn' zone. Within the C submember of the BIF is a 2-18 foot thick sill referred to as the BIF Sill. Because it is metamorphosed by the SKI and PRI, the sill is inferred to be time synchronous with the Logan Sills. The BIF Sill generally contains low Cr contents. In the Serpentine area, up to twelve additional sills are present within the A and B submembers of the BIF and are referred to as EXTRA BIF Sills. These sills appear to have been formed by the bifurcation/emplacement of either the BIF Sill or VIRG Sill along a highly fractured zone associated with the Grano Fault. The EXTRA BIF Sill has high Cr contents (400 ppm Cr in one sample). Near the base of the Virginia Formation are two sills that are referred to as VIRG Sill. These sills have been previously described by Gundersen and Schwartz (1962), and Severson (1991). The VIRG Sill is chemically similar to the EXTRA BIF Sill (both also have high Cr contents). A pre-SKI/PRI age (Logan Sill age?) is also inferred for the VIRG Sill. However, the difference in chemistry between the BIF Sill and VIRG Sill may indicate that each sill group may have been emplaced during two separate events. Also located near the base of the Virginia Formation are discontinuous patches of a graphitic argillite that contain regular fine-laminae of pyrrhotite. It is referred to as the BDD PO member of the Virginia Formation. Massive sulfide mineralization at the basal contact is often in close proximity to areas where the BDD PO is in direct contact with the Complex. These spatial relationships suggest that the BDD PO may represent an excellent local sulfur source. However,
available sulfur isotope values do not wholly support this concept and addition sampling may be necessary before an *in situ* sulfur source can be ruled out.

**SUMMARY OF HANGING WALL ROCKS**

Three different types of hanging wall rocks are present as inclusions within the SKI. The three varieties are: 1) basalt inclusions that are presumably correlative with basalts of the North Shore Volcanic Group; 2) quartzite inclusions (Nopeming Fm?) that are associated with the basalt inclusions; and 3) magnetic CC inclusions that are similar to rocks exposed in the Colvin Creek Hornfels and may represent basalts of the North Shore Volcanic Group. The basalt inclusions and CC inclusions are dissimilar and similar in various aspects. Whole rock chemistry suggests that the two are dissimilar; however, spider diagram profiles suggest a crude similarity. The conflicting nature of the two has not been resolved in this investigation, and the CC inclusions remain an enigmatic rock type. The ‘INCL’ within the H1C is a rather large CC-type inclusion.

Within the Serpentine area, the configuration of basalt inclusions close to the basal contact, and basalt in direct contact with Virginia Formation suggest an anomalously thin Virginia Formation (only 80 feet thick in one drill hole). These observations together imply that a pre-Keweenawan erosional surface developed on the Virginia Formation in the Serpentine area prior to deposition of the North Shore Volcanic Group. A basalt-filled valley within the Virginia Formation is envisioned as a possible explanation of these features. Interestingly, quartzite inclusions (Nopeming Fm?) are also common within, and to the immediate north of, the zone of anomalously thin Virginia Formation.

**SUMMARY OF GEOCHEMISTRY**
Spider diagrams and X-Y plots pertaining to SKTS units, footwall rocks, and hanging wall rocks are used to determine if the units can be distinguished on a chemical basis. Pertinent observations related to how specific units compare and differ are listed below.

1. In most cases in the spider diagrams, all of the samples collected from a specific SKTS unit exhibit the same profile, and in turn, all of the profiles from that unit lie within a very tight field. In addition, the profile fields for each of the individual SKTS units often show some variation relative to the other SKTS units. This is generally expressed by a change in the relative plotted position of the profile field in the spider diagrams due to the relative enrichment or depletion in incompatible elements. For example, the BAN Unit plots much higher than the BH Unit due to higher incompatible element values associated with the BAN Unit (related to more contamination of the melt due to assimilation of larger volumes of footwall rock?). Because each of the profile fields for the SKTS units plots in relatively different positions, spider diagrams can be used to discriminate between the various units of the SKTS. This is an important observation and can be utilized to further categorize SKTS units. However, there is also some overlap between each of the fields and caution is advised when spider diagram profiles are solely used to discriminate between SKTS units. A second important feature of how SKTS units group according to chemistry is that it confirms the geologic correlations established in this investigation. For example, all samples collected from material consistently referred to as the ’MAIN AGT Unit’ show the same spider diagram profiles.

2. The uppermost units of the SKTS are subdivided into two major groups, AT&T and AT(T) units, even though both consist of a ‘homogeneous sea’ of troctolitic rocks. The only difference between the two units is that the AT(T) Unit contains more anorthositic troctolite than the underlying AT&T Unit. Spider diagram profiles are exactly the same for both units (four samples) and confirm that static conditions were prevalent during crystallization of the upper portion of the SKI.

3. Spider diagram profiles of rock units collected from the Highway 1 Corridor inclusion are distinctly different from all of the other SKTS units. This confirms the exotic nature of the
Highway 1 Corridor rock package. Each of the HIC units exhibit correspondingly tight fields, each of which is different than the other.

4. X-Y plots are not particularly instrumental in discriminating between the SKTS units. All of the troctolitic rocks fall within the same general field, but some units are also within distinct fields. Units that plot within distinct fields relative to all other troctolitic rocks of the SKTS are the BAN, AT&T-AT(T), and AN-G GROUP units. The ultramafic layers of the SKTS also plot within a field that is distinct, and more primitive, than the field for the troctolitic rocks. Units that plot within the ultramafic field are the U1, U2, U3, and BU units. Samples collected from each of these units plot as isolated points that are scattered throughout the ultramafic field. Ultramafics from the U2 Unit are generally the most primitive (highest MgO content) of this group based on a limited data set.

5. The effects of contamination to the melt due to assimilation of footwall rocks are also confirmed by the geochemical overlap of the BU, U3, and BIF units. Spatial relationships suggest that massive oxides in the BU and U3 units were derived from intruded and assimilated BIF that was capable of generating an oxide-rich 'restite.' Similar spider diagram profiles for these units confirms this empirical relationship.

6. Samples collected from basalt inclusions cluster within a small field in the X-Y plots. This observation indicates that geochemistry can be used to distinguish hanging wall rocks from rocks of the Complex. This is an important consideration with regard to fine-grained zones within the Complex that are not always easily identified as either inclusions of basalt or inclusions of earlier chilled material. Two slightly different spider diagram profiles are apparent for the basalt samples collected in this investigation. The reason for, or importance of, this difference is unknown at this time.

7. The nature of the CC-type inclusions is still unresolved. The 'INCL' Unit of the Highway 1 Corridor rock package is inferred to be a CC-type inclusion due to its high magnetite content. To date, the ‘INCL’ and other CC inclusions (data from Severson and Hauck, 1990; and Severson, 1991) are different than ‘typical’ basalt inclusions in some aspects (dissimilar whole rock chemistries). However, both groups are also similar in other aspects (somewhat
8. A few surprises were encountered in sampling specific rock units during the course of this investigation. One surprise was that material classed as 'norite adjacent to, and grading into, a large basalt inclusion' exhibited a spider diagram profile that was an exact match to basalt inclusion profiles. This sample also grouped with the other basalt inclusion samples in all the X-Y plots. The second surprise was that material classed as a 'BU Unit pyroxenite' exhibited the same chemistry and spider diagram profile as the underlying BIF (note that the BU Unit grades into recognizable BIF with depth). In both cases, the surprise turned out to be strongly recrystallized zones of hanging wall rock and footwall rock, respectively. This indicates that geochemistry can be used to help 'sort out' differences between country rock that grades into strongly recrystallized country rock, that in turn, grades into Complex rocks.

9. Two sills are present within the footwall rocks and are referred to as BIF Sill and VIRG Sill. Geochemistry indicates that the sills are vastly different - both exhibit dissimilar spider diagram profiles and dissimilar fields on the X-Y plots. Both sill groups are inferred to be time synchronous with the Logan Sills, but their dissimilar chemical nature suggest that they may have been emplaced during two separate events. On the X-Y plots, the BIF Sill samples generally plot in a tight cluster; whereas, the VIRG Sill samples and EXTRA BIF Sill sample plot along a linear trend (differentiation trend?).

10. PGE analyses conducted on a multitude of rock types and units within the SKTS indicate that the U3 Unit, and to a lesser extent the PEG Unit, show the most promise of hosting a PGE deposit. The plotted position of both of these units on PGE petrogenetic plots (Figs. 48, 49 and 50) suggest that they show the most promise of hosting a PGE deposit. Within the U3 Unit, high PGE values are associated with both high Cu and Cr values on a 1:1 basis; however, high PGE values are also commonly associated with low Cu and Cr values on a 1:1 basis. There is no definable pattern for these 1:1 associations.
NATURE OF PGE MINERALIZATION IN THE SKI

The U3 Unit is the dominant host of anomalous PGE values (>100 ppb) throughout most of the SKI. However, significant PGE values (>1.0 ppm) are restricted to the U3 Unit in the Birch Lake Deposit even though the geology of the U3 is fairly constant throughout the SKI. Development of any model to explain PGE enrichment within the U3 must take these differences into account. Throughout most portions of the SKI, the U3 Unit is unique in that it often contains discontinuous massive oxide pods and discontinuous high Cr contents. The massive oxides are empirically related to intruded and assimilated BIF that was capable of generating an oxide-rich 'restite.' The 'restite' may have then acted as a trap that was capable of concentrating Cr (as well as Ti) from the magma. Because of these initial conditions the U3 Unit may have, in turn, acted as a stratigraphic trap and concentrated remobilized PGE. Upward-moving, Cl-rich, hydrothermal solutions may have been the transporting agent that concentrated PGE in the U3 stratigraphic trap. A model involving PGE transfer by Cl-rich solutions has recently been proposed by Boudreau and McCallum (1992).

The model of Boudreau and McCallum (1992) reasonably explains why anomalous PGE are so common to the U3 Unit, but it does not explain why significantly higher PGEs are restricted to specific areas, e.g., Birch Lake Deposit. A variation on the 'Boudreau and McCallum model' is proposed in this investigation to explain these differences. It is similar to the 'Boudreau and McCallum model' except that Cl-rich solutions are envisioned to have been more concentrated in fault zones. Wherever increased fluid flow associated with open fault zones encountered the proper stratigraphic trap, significant PGEs were deposited relative to areas outside of the fault zones. An intersection of the proper stratigraphic trap (U3 Unit with massive oxides, sulfides, and high Cr contents) and the proper channelway to concentrate PGE-pregnant Cl-rich solutions (Birch Lake Fault) reasonably explains why significant PGE values are present in the Birch Lake Deposit.
CONCLUSIONS

A voluminous amount of data was obtained on the igneous stratigraphy of the South Kawishiwi intrusion of the Duluth Complex. A heretofore unknown igneous stratigraphy (SKTS) is established and correlated in over 120 drill holes. However, the stratigraphic package is not consistent throughout the entirety of the intrusion.

There are several stratigraphic variations that have to be viewed on a 'deposit to deposit' basis. Because specific units are present in one Cu-Ni deposit area does not mean that all of the same units are present elsewhere, e.g., Dunka Pit Cu-Ni deposit versus the Maturi Cu-Ni deposit. In essence, the lower portion of the SKI is compartmentalized along the length of the intrusion. This relationship suggests that the lowest units of the SKI were emplaced into several restricted chambers that eventually coalesced with continued addition of magma. In contrast, the upper units of the SKI are more homogeneous and appear to have crystallized within a progressively-developed open magma chamber. The exact age relationships of each of the SKTS units to each other has not been established.

A second important aspect of this investigation is that it documents dissimilar stratigraphic packages in the South Kawishiwi and Partridge River intrusions based on hundreds of drill hole correlations. The data also suggest that the PRI is older than the SKI.

RECOMMENDATIONS

An attempt was made to categorize the entire SKI in terms of igneous stratigraphy and geochemistry. However, in view of the segmented nature of the lower portion of the SKTS, the geochemical comparisons presented in this investigation are inadequate. Continued geochemical sampling of SKTS units throughout the entirety of the SKI is paramount to deciphering its complicated history. Also, precise age dating of the various SKTS units are instructive in unraveling
age relationships. All of these points are critical to our understanding of the complexities that are inherent to the Duluth Complex.
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The following files are given in Appendix A on the floppy diskette (1.2 mb) in the back pocket of this report:

**SOKALITH.WK1** (130,190k, 06-30-93, 12:38p)
Drill hole locations and lithologic breaks: see next page for columns and abbreviations used in SOKALITH.WK1

**SOKSORT.WK1** (134,495k, 06-18-93, 1:10p)
Whole rock chemical data (this investigation): results are grouped according to the rock unit and rock type.

**SOKAWR.WK1** (388,101k, 09-21-93, 3:30p)
Whole rock chemical data (previous analyses): results are grouped according to drill hole (corresponding rock unit and rock type are also listed)

**SOKAPM.WK1** (328,380k, 09-21-93, 3:22p)
Precious metal chemical data (previous analyses): results are grouped according to drill hole (corresponding rock unit and rock type are also listed). Note that some of the sampled intervals are repeats of the SOKAWR.WK1 data file.

**DNRSORT.WK1** (226,765k, 05-18-93, 2:29p)
Whole rock chemical data (previous analyses): results are grouped according to rock unit. Note that this data file is a 'cleaned' version of the SOKAWR.WK1 data file. Sampled intervals that cross contacts are eliminated. Sampled intervals with poor whole rock totals (<98%) are also eliminated.

NOTE: Paper copies of SOKALITH.WK1 available upon request.
COLUMNS AND ABBREVIATIONS USED IN SOKALITH.WK1

Drill Hole = drill hole number

Deposit = area of extensive exploratory drilling: Mnmax = Minnamax/Babbitt; Serp = Serpentine;
Mat-S.Rd = area between Maturi and Spruce Road; and Fernberg Tr = Fernberg Trail Area

S-T-R = Section-Township-Range

UTM-East = East UTM coordinates (in meters)

UTM-Northing = North UTM coordinates (in meters)

Inclin. = Drill hole inclination in degrees (and direction for inclined holes)

Elev. (ft.) = Drill hole collar elevation (in feet)

T.D. (ft.) = Total depth of drill hole (in feet)

Complex (ft.) = Interval of drill core containing rocks of the Duluth Complex (the first number of
the interval generally corresponds to the amount of overburden material)

Virginia Fm. (ft.) = Interval of drill core containing rocks of the Virginia Formation

Biwabik Iron-Fm. (ft.) = Interval of drill core containing rocks of the Biwabik Iron-formation

Sill (ft.) = Interval of drill core corresponding to the BIF Sill within BIF submember C (more than
one sill denotes the presence of the EXTRA BIF Sill)

Pokegama Fm. (ft.) = Interval of drill core containing the Pokegama Formation (in feet)

Giants Range (ft.) = Interval of drill core containing granitic rocks of the Giants Range Batholith

Logged? = Denotes the NRRI person, or persons, that relogged the specific drill hole
MJS = Logged by Mark J. Severson
MJS-91 = Logged by Mark J. Severson prior to this investigation
LMZ = Logged by Lawrence M. Zanko (Zanko et al., 1994)
LMZ/MJS = Logged by Lawrence M. Zanko and Mark J. Severson (as above)
MJS* = Scanned by Mark J. Severson for major lithologic breaks
nc = no core available for relogging

(600-650) = Denotes a drill core interval where a specific formation is present as one inclusion

((600-650)) = Denotes a drill core interval where many inclusions of a specific formation are present

79?-274? = Denotes a drill core interval where original drill log states that a specific formation is
present; however, this portion of drill core is no longer available for inspection
79?-274 = Denotes a drill core interval where original drill log states that a specific formation is present; however, the upper portion of drill core is no longer available for inspection.

79-274? = Denotes a drill core interval where original drill log states that a specific formation is present; however, the lower portion of drill core is no longer available for inspection.